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Watershed Assessment in the Southern Interior of British Columbia: Workshop Proceedings

March 9–10, 2000

Penticton, British Columbia, Canada

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D.A.A. Toews and Stephen Chatwin (editors)

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PREFACE

In 1995, British Columbia implemented a Forest Practices Code that made watershed assessment mandatory in community watersheds and on selected high-value fish streams. A guidebook was published in 1995 to prescribe the method by which watershed assessment was to take place. The hydrologists who developed this guidebook based the procedure on their professional opinions of the manner in which hydrologic processes are altered by road-building and logging. There was a need to verify the guidebook with research. A research program was put in place in the Nelson Forest Region to verify various concepts that were incorporated into the guidebook. Also, research programs were put in place elsewhere in the interior to better understand hydrologic processes that are occurring in interior watersheds. This workshop has been organized to update those who do the assessments and those who use the assessments on the most recent research findings.

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Watershed Processes in the Southern Interior of British Columbia: Background to Land Management

MICHAEL CHURCH AND JUNE M. RYDER

ABSTRACT

The factors that govern morphology and processes along stream channels are the amount and timing of water delivery to the channel, the amount and calibre of sediment delivered, the gradient over which the channel flows, and the conditions of bank vegetation and wood supply to the channel. A fundamental distinction must be recognized between low-order, headward drainage basins and larger, higher-order ones. Headward basins are the source of channeled streamflow and much of the sediment that moves through the drainage system. Trunk streams combine drainage from many headward channels. Headward channels are coupled to slopes that deliver sediment inputs directly; trunk streams are buffered from adjacent slopes by a valley flat. Headward channels are subject to episodic major disturbance, usually in the form of landsliding. Trunk channels experience the attenuated effect of disturbances at many places in the headwaters. Sediment delivery and onward transfer occur frequently in such channels. Exceptions occur. Headward channels sometimes are flat, and may drain extensive wetlands. Conversely, many valley streams are incised into and at least partially confined by high banks composed of Pleistocene sediments. Diagnosis of land surface conditions and actions to ensure soil and landscape stability should be focused upon hillslope stability in headward drainage basins. Along valleys, the focus of attention must be the stream channel and riparian zone. Consequently, hydrological watershed assessment is an appropriate management tool in relatively small, upland drainage basins, but in larger drainage systems the major management tool for uncoupled channels should be stream channel stability assessment.

INTRODUCTION

Morphology and processes in a stream channel are the outcome of specific governing conditions, of which the principal ones are the amount and timing of water delivered to the stream channel, the amount and calibre of sediment delivered to the channel, the gradient over which the water flows, and the conditions of bank vegetation and (in forests) supply of wood to the channel (see Church 1992). Gradient is very important, for it determines the power of the water as it moves downslope, and hence the ability of the stream to move sediment and modify its channel.

These conditions change systematically through the drainage network (Schumm 1977, reviewed in Church 1992). Tributary confluences create step increases in area drained, and hence in water flows. Because of variations in runoff timing between tributaries, flows become relatively less variable downstream. The gradient of the channel declines more or less systematically downstream as well. The consequences for sediment transport are complex. The ability of the stream to move large material (competence) declines as gradient declines—so large material is left behind—even as the capacity of the river to move volumes of sediment increases. These changes have important consequences for channel morphology, for channel stability, and for aquatic habitat.

For land-management purposes, a fundamental distinction must be recognized between headward, low-order drainage basins and larger, higher-order basins (Figure 1). The former are often characterized by relatively steep slopes that are coupled directly to steep stream channels; the latter include

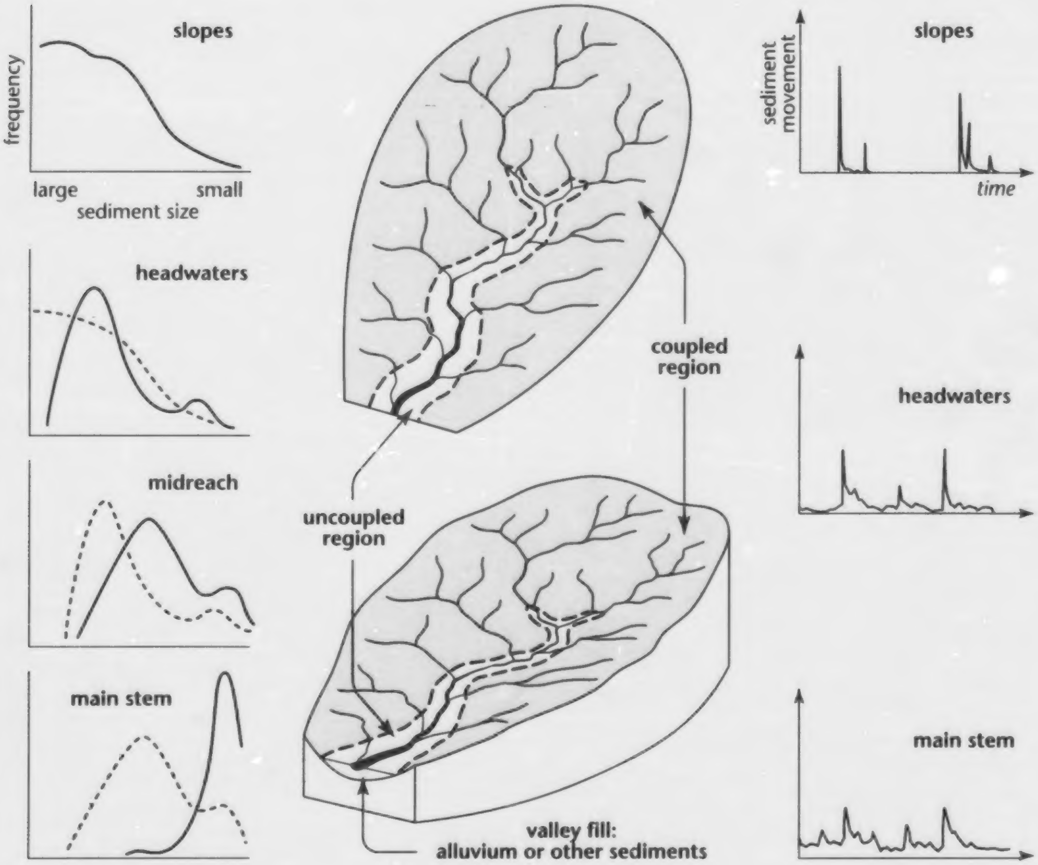

FIGURE 1 *Map and schematic views of a drainage basin to illustrate the concept of "coupling" between a stream channel and adjacent hillside slopes. On the right side of the diagram are seasonal hydrographs to illustrate the attenuation of variations in flow down the system. On the left side of the diagram are schematic graphs of characteristic grain size distributions of channel bed material through the system. In each graph, the next upstream distribution is shown (dashed line) so the intervening modification by stream sorting processes may be directly appraised.*

trunk stream channels on low gradients that are buffered from adjacent slopes by a valley flat, which is often a floodplain (Rice and Church 1996). (However, an important exception occurs in interior British Columbia where headmost drainage often occurs on uplands of modest relief.) Headward drainage basins are the source of channeled streamflow and of much of the sediment—inorganic and organic—that moves through the drainage system. In the long run, they export sediment; but, in the short run, substantial accumulations may occur along steep channels. Headward channels constitute the large majority of all stream channels, by number and by cumulative length (Figure 1). Trunk streams combine drainage from many headward channels. Part of the sediment load that they receive is stored for more or less extended periods along the valley in alluvial fans and floodplains. The nature of fluvial disturbance is different between these two landscape elements.

RUNOFF GENERATION

Streams exist because of the need to evacuate water from the surface of the land. Watershed processes are forced by the pattern of runoff. The incidence of runoff is controlled by weather at synoptic, seasonal, and longer-term scales. However, the timing and magnitude of runoff are also influenced by factors such as topography (including surface elevation and slope steepness), by the permeability of surface materials, and by the vegetation cover. The latter two factors may exhibit large variability at scales of only a few metres.

In interior British Columbia, high runoff is promoted by four weather situations. Heavy rain may occur during summer convectional (often thunder) showers or during frontal precipitation, especially in autumn. What constitutes "heavy rain" depends on the duration of rainfall. Convectional showers typically create the highest rates of rainfall, but only for short periods (precipitation exceeding 5 mm in 10 minutes would be relatively heavy), whereas frontal storms can accumulate large total rainfall by long persistence (greater than 50 mm in 24 hours). In fact, long-duration storms of lower average precipitation intensity often produce the greatest runoff because precipitation continues for much longer than the time for runoff generation and the soil may become thoroughly saturated during such storms. Summer showers often fall onto dry soil and create a relatively small runoff response. However, convectionally augmented rain on fronts during large summer storms may create significant floods and mass wasting.

A third significant weather situation is snowmelt, which creates high runoff between April and June. Timing depends on location in the province, topography, and annual seasonal weather patterns. Because of the energetic limitations of melt rate, however, snowmelt does not create the potentially highest flows (Church 1988). Finally, rain-on-snow, when snowmelt and rainfall-generated runoff occur simultaneously, may create the largest flows of all. Contrary to common belief, the energy for snowmelt comes not from rainwater (the specific energy of water being only a small fraction of the energy of fusion), but from turbulent energy exchange over the snow surface and from condensation of moisture from the atmosphere onto the snow surface. Hence, storms accompanied by high winds, which facilitate these processes, are most prolific.

Topography substantially modulates runoff patterns. Interior British Columbia is a land of plateaus and mountains. In plateau areas, water storage on the upland surface in bogs and small lakes (including numerous beaver ponds) may substantially moderate runoff rates and prolong seasonal flows in summer. An important contrast occurs between plateaus and mountains at the time of snowmelt. In mountains with long, continuous slopes, the snowline retreats upward, and from southerly to northerly exposures, in a more or less orderly fashion, producing a prolonged, moderate freshet. The highest mountains carry glaciers that sustain meltwater runoff through the summer. In contrast, in plateau country, a large portion of the upland surface experiences snowmelt within the same time period, so a relatively short, high freshet may occur downstream, depending upon how much water can be retained on the upland.

Extreme runoff events are rare in individual headwater streams because the incidence of extreme water input is rare at any particular spot in the landscape. The most extreme rain, even in a large storm, is relatively localized in the landscape (Figure 2). However, extreme runoff events are common regionally because many storms deliver heavy precipitation somewhere along their path. Downstream, channels receive flows from many tributaries (i.e., from a large upstream area), so they more frequently experience comparably severe events. But, since flood waves disperse downstream, runoff is comparatively less extreme farther from headwaters (see the sketched hydrographs in Figure 1).

Runoff commences on hillslopes that are usually mantled by thin surface materials composed of till or colluvium. Rock outcrops are common. Under forest cover, the surface usually consists of a permeable forest soil (O horizons over weathered till or loosely packed colluvium), but permeability generally decreases with depth. Water infiltrates the soil, then moves laterally downslope over relatively impermeable materials (Figure 3). It may seep

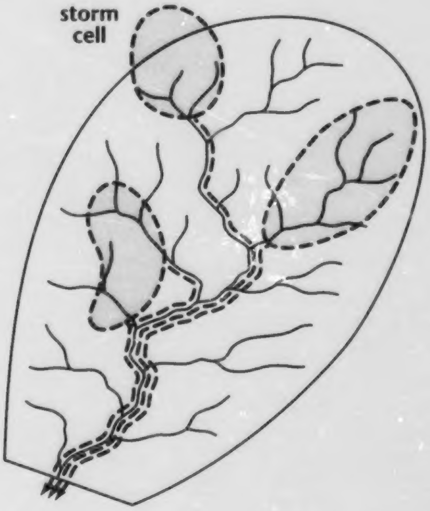

FIGURE 2 *Schematized occurrences of the incidence of heavy event precipitation, located on a drainage basin map to emphasize the localized nature of individual events and the common effect in trunk channels downstream.*

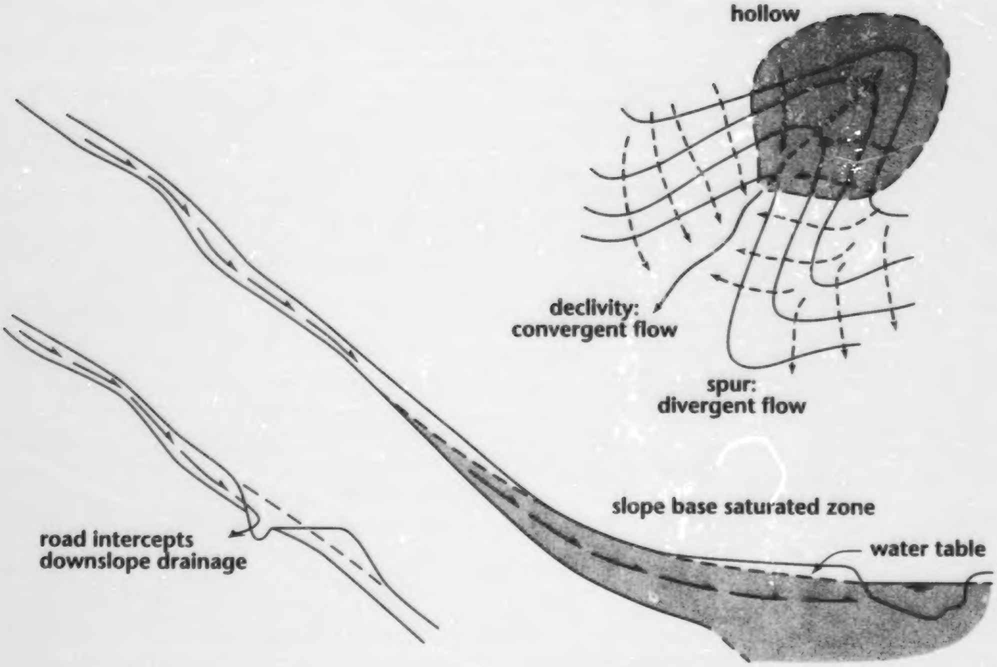
hollow
declivity: convergent flow
spur: divergent flow
slope base saturated zone
water table
road intercepts downslope drainage

FIGURE 3 *The pattern of hillslope drainage, in profile and in plan, and a profile to show the interception of downslope subsurface drainage by midslope roads.*

along the bedrock surface or along the top of unweathered till or other compact, fine-grained material. It commonly exploits root channels, animal burrows, and other connected discontinuities in the soil body (e.g., DeVries and Chow 1978). The result is generally rapid, shallow subsurface flow wherever there is any appreciable topographic gradient (cf. Whipkey 1965; Beven and Germann 1982). As the result, water reaches channels relatively quickly and the event hydrograph is of short duration, but features a relatively sharp rise and high peak.

Overland flow is not common on natural land surfaces (because undisturbed forest soils have infiltration capacity that is even higher than extreme precipitation rates), but occurs if the land surface is effectively impermeable, as on rock outcrops, exposed impermeable soils (usually old landslide scars), hydrophobic (e.g., peaty) soils following summer drought, frozen soil, and compacted soil (e.g., paths). The result is an even more peaked hydrograph and "flash floods."

Water runs directly downslope at rates proportional to the gradient and to the hydraulic conductivity of the flow path. It drains away from spurs and ridges, and concentrates in depressions and slope-base concavities (Figure 3), where the water table is at relatively shallow depth. Where the water table intersects the surface, seepage and springs occur. This initiates surface streams. On upland surfaces, low gradients create poor drainage conditions, so standing water frequently occurs on the surface in bogs and ponds, and runoff may be highly delayed and long and drawn out.

Headwater channels receive water and sediment inputs directly from adjacent slopes and streambanks. Where adjacent slopes are steep, direct inputs of sediment may occur from well upslope and may include boulders and even larger blocks. In mountain terrain, headwater channels are usually steep and flanked by steep slopes. In the interior, headwaters may be on upland surfaces of low relief, but most streams steepen dramatically when they flow off the plateau surface toward the valley trunk streams. In this discussion, attention will be focused on steep reaches because this is where most sediment recruitment occurs and most land management problems arise.

Steep, headward reaches are subject to episodic major sediment delivery, usually in the form of landsliding. Studies of slope erosion in the Pacific Northwest, with results from both coastal and interior sites, yield the range of results shown in Table 1. (The figures are generalized to order of magnitude values based on the results of many studies.) When account is taken of the limited area occupied by landslides—typically less than 1% of the land surface—it is apparent that the episodic landslides themselves are the most significant means of sediment delivery downslope. However, lesser processes also contribute to recharging hillslope hollows and gullies over decades or even centuries, which may eventually lead to a major failure.

As the consequence of storm and precipitation characteristics, meteorological forcing of such failures is relatively rare at any particular place in the landscape, although it is common regionally. Once in the channel, large debris may remain for a long time, since ordinary stream flows are incapable of moving it. The result is a stable step-pool structure (Figure 4), prevalent in channels with gradient greater than about 4% (Grant et al. 1990; Chin 1999), often reinforced by wood steps (Keller and Swanson 1979). The steps trap finer material. Hence, channels may accumulate stores of sediment over

TABLE 1 *Sediment mobilization and yield from hillside slopes*

	Mobilization rate		Yield rate to stream channels	
Process	**Forested slopes**	**Cleared slopes**	**Forested slopes**	**Cleared slopes**
Normal regime				
Soil creep (including animal effects)	$1\ m^3/km/y^*$	2x	$1\ m^3/km/y^*$	2x
Deep-seated creep	$10\ m^3/km/y^*$	1x	$10\ m^3/km/y^*$	1x
Tree throw	$1\ m^3/km^2/y$	—	—	—
Surface erosion: forest floor	$<10\ m^3/km^2/y$		$<1\ m^3/km^2/y$	
Surface erosion: landslide scars, gully walls	$>10^3\ m^3/km^2/y$ (slide area only)	1x	$>10^3\ m^3/km^2/y$	1x
Surface erosion: active road surface	—	$10^4\ m^3/km^2/y$ (road area only)	—	$10^4\ m^3/km^2/y$ (road area only)
Episodic events				
Debris slides	$10^2\ m^3/km^2/y$	2-10x	to $10^4 m^3/km^2/y$	to 10x
Rock failures (fall, slide)	No consistent data: not specifically associated with land use			

* These results reported as m^3/km channel bank. All other results reported as m^3/km^2 drainage area. Results are generalized from a table that originally appeared in Roberts and Church 1987.

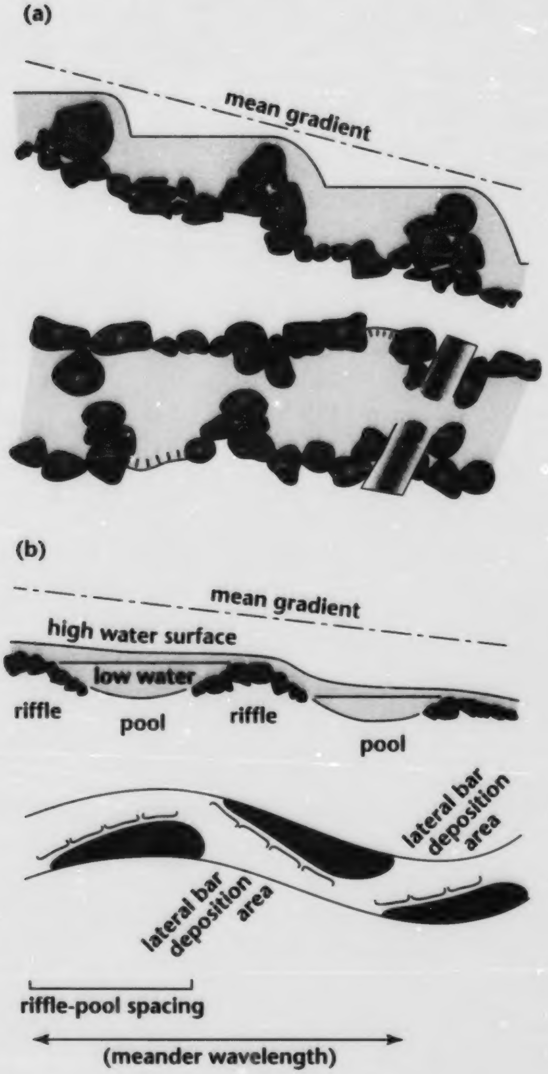

FIGURE 4 *The characteristic step-pool structure of steep headwater channels (a), and the riffle-pool structure of gravel-bed streams along the valleys (b).*

periods varying from years to centuries (e.g., Megahan 1982), and then release substantial portions of it during an extreme event. Sediment movement down steep channels often occurs as debris flow because, once the framework boulders begin to move, all the material in the channel becomes unstable. Debris flows may be triggered by landslides (which dam the channel for a short period and accumulate an extreme charge of water), by extreme storms (usually after a prolonged wet period), or, rarely, by seismic shaking (see VanDine 1985 for a general review). In southern interior British Columbia, debris slides and flows often occur during the characteristic early summer wet period, when extreme, convectively augmented rainfall may occur locally (a useful inventory of events and analysis are given by Toews

1991). Often, contributory runoff is augmented by or derived primarily from snowmelt.

Mass wasting processes deliver to the stream channel material with a wide range of sizes, from silts and clays to the largest detached blocks (see material texture sketches in Figure 1). Finer material (up to medium gravel) can, of course, be mobilized in the channel by much smaller flows than those necessary to move the large debris. This material (termed "wash material," because it is easily washed downstream and does not persist in the channel bed) is moved by normal high flows sufficiently frequently that it is commonly supply-limited. Consequently, significant quantities are moved only when they are available in the channel bed, commonly for a season or a few seasons after a landslide into the channel, or during spring runoff after winter's freeze and thaw. Glacial delivery of fine material is, of course, much more persistent. At the other extreme, upland channels on low gradients may transfer very little material other than particulate and dissolved organic matter.

This picture of headwater channel behaviour, emphasizing the episodic nature of significant sediment movement, reconciles the superficially contradictory observation that they are the source of most of the sediment and other debris that moves through stream systems, and yet they are also the source of high-quality water supplies.

A trunk valley channel receives water and sediment from many headward channels. Such channels experience the integrated effect of episodic disturbance at many places in the headwaters. Sediment delivery and significant onward transfer occur frequently in such channels, but the relative severity of individual events is attenuated by the dispersive effects of increasing travel distance from the source (of both water and sediment). Sands and gravels, evacuated from headward channels as wash material, become the normal bed material on the lower gradients, but can be remobilize by normal high flows. Significant bed-material transport occurs during frequently recurring snowmelt and rainstorm flood events—on average once or twice a year in gravel-bed reaches, and much more frequently in sand-bed channels.

Much of the sediment delivered from headwater channels—including the largest material—is deposited at slope base along the edge of trunk valleys, in the form of debris flow fans or alluvial fans (Figure 5). Farther down the system, material is stored in channel bars (Figure 4) and floodplain deposits that subsequently serve to buffer the channel from the immediate effects of processes on adjacent slopes. Floods may re-entrain material previously delivered by fluvial processes, so river bars and banks are major loci of sediment pickup and the result may be continual change in river morphology. Along many valleys, as well, there remain substantial deposits of Pleistocene glacial materials that form additional, sometimes abundant sources of sediment to the river (e.g., Ryder and Fletcher 1991).

With generally declining gradient downstream, competence limitations sort the stream-transported material, so that the largest is left behind and a gradient in material size is established down the system. Processes of channel filling and cutting in the floodplain, facilitated in the forest by the formation and dissipation of log jams (Keller and Swanson 1979; Hogan et al. 1998), progressively create a complex channel and wetland landscape that forms superior habitat for salmonid fish and many other aquatic and semi-aquatic creatures. Paradoxically, the onward movement of sediments, which creates continual change along the channel system, is an essential process for the

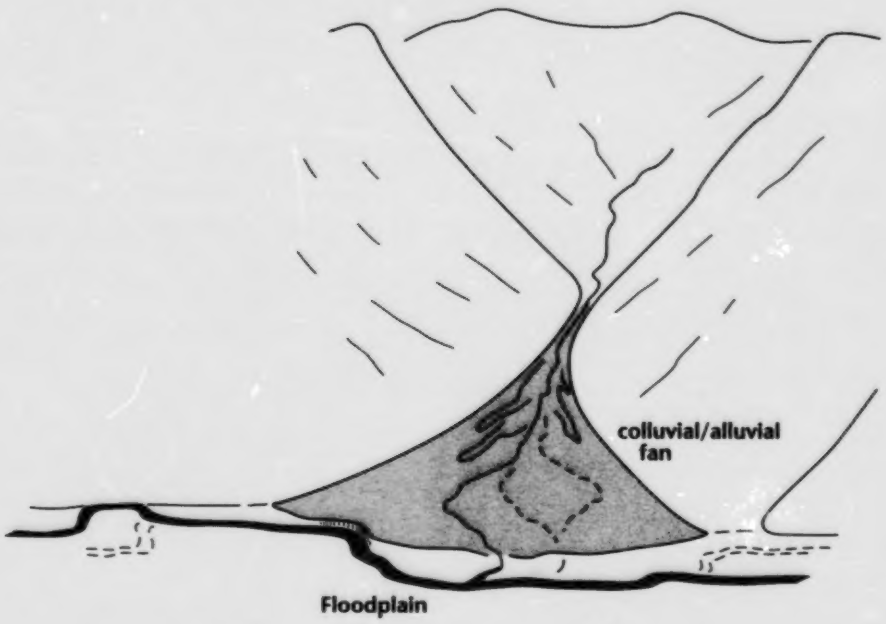

FIGURE 5 *Sediment storage at the transition from headwater to valley-bottom reaches in the form of colluvial or alluvial fans and floodplain deposits.*

creation and maintenance of this habitat. On the other hand, where the channel is incised and confined within substantial Pleistocene deposits, it usually maintains a simple morphology, with relatively little fluvial sediment storage. Such reaches generally provide much less productive habitat.

DISTURBANCE DUE TO LAND USE

Because of the distinct character of water flows and sediment transfer between headwater and valley-floor streams, disturbances associated with land use influence each environment in distinct ways (cf. Whiting and Bradley 1993; Grant and Swanson 1995). Appropriate monitoring and management activities are different.

In headwaters, land use on adjacent slopes may change both runoff and sediment delivery to the stream channels. Changed runoff to a channel may change the incidence of "extreme" (channel-evacuating) events, while a changed rate of sediment delivery to the channel may change the size and frequency of recurrence of major sediment-evacuating events.

The step structure formed by interlocked large clasts and wood in many channels makes them relatively insensitive to incremental changes in runoff.[1] Similarly, on uplands the prevalent low gradients and large areas of standing water absorb incremental changes with relatively small changes in flow regime. Significant, destabilizing changes to runoff most often are the consequence of changed drainage structure, almost entirely associated with road construction and creation of skid trails (Megahan 1987; Montgomery 1994). Major causes are diversions via road ditches, redirection of subsurface drainage to surface drainage at road cutbanks (Figure 3), and the establishment of surface drainage along skid trails and yarding tracks.

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[1] Zimmermann, A. and M. Church. 2001. Channel morphology and bed stresses during spring runoff in a step-pool channel. Geomorphology. In revision.

Changed sediment delivery rate from mass wasting may be the consequence of harvesting on tenuously stable hillside slopes, poor harvest practices in and around gullies, and failures in road sidecast. Substantial mobilization of fine sediment may occur along ditches, from road and skid track surfaces, and from gullying in sidecast (reviewed in Montgomery 1994; of regional relevance is Anderson and Potts 1987). Where these sediments reach a slope-base flat, they may go back into storage, but along steep, headwater channels, they usually land directly in the channel.

The circumstances surrounding disturbance of both runoff and sediment supply in headwater streams represent a relatively fortunate situation because all of them are well understood and can be avoided by the implementation of suitable land classification and forest engineering practices, if there is a will to do it. The single most important preventive action is high-quality road management, including route selection, engineering, and operational maintenance.

In valley bottoms, incremental runoff and/or changed runoff timing may increase the peak flows, while increased sediment delivery from upslope may create significant aggradation and may destabilize channels at slope base and beyond.

Incremental runoff in areas from which trees have been removed is a consequence of reduced transpiration (reviewed in Hetherington 1987) and snow loss (by sublimation or evaporation from trees), hence Equivalent Clearcut Area (ECA) may be important. However, summary effects on late-winter snow accumulation may be complex due to wind effects and the possibility for overwinter melt (Hetherington 1987). From the perspective of flood flows, a major effect of the changed water budget works through increased soil moisture storage levels before storms (Harr et al. 1975; Hetherington 1987). This would lead to larger runoff during the first storms after a prolonged dry period (typically, early autumn storms), and to increased peak runoff during moderate floods. On the other hand, water yield from major storms occurring on already thoroughly wetted land are unlikely to be affected in a major way. In the interior, spring rain-on-snow may yield notably high flows (MacDonald and Hoffman 1995), especially where the ground remains frozen.

Changed runoff timing is the consequence of changed drainage pattern and earlier upslope snowmelt following land clearance. Because of the dendritic structure of the drainage network, with successive confluences of flow from different parts of the drainage basin, and because of the effect of elevation and exposure on the normal course of snowmelt, the summary effect on runoff timing of road construction and land clearance depends sensitively on where, in the drainage basin, the activities occur. To make a simplified example, upslope road construction and clearance may accelerate runoff timing within storms, and advance seasonal snowmelt so that upland streamflows catch up with runoff from lower parts of the basin, resulting in substantially increased flood flows downstream. On the other hand, similar activities at low elevation may have no comparable effect. On the land, these effects—especially storm runoff formation—are exceedingly sensitive to such highly variable natural factors as land surface detention, soil hydraulic conductivity, and channeled flow resistance, so that attempts to study them have often led to complex outcomes that are difficult to interpret.

Changed sediment delivery to valley streams results from upslope mobilization of sediment and from direct disturbance of the channel bed and/or banks along the valley reach. The most sensitive zone in the fluvial landscape is the slope base region where much of the sediment delivered from upland channels is first deposited. Persistent aggradation on fans and in the upstream parts of trunk valleys may create highly unstable stream channels there. However, control of sediment sources relatively rapidly creates degradation and stream channel incision through the deposits. Farther down the system, strongly dispersive effects associated with the relatively slow onward transfer of streambed material (the larger material in the sediment load) spreads these trends out over longer periods. On larger rivers, it is often difficult to determine the ultimate source of transient instability, which may persist at modest intensity for many years or decades.

In contrast to streambed material, fine sediments move quickly through the stream system. The effects of headwater yield of fine sediment are quickly reflected in reduced water quality and streambed siltation for a long distance downstream. However, the elimination of sources may clear up the system relatively quickly as well. Control measures must be taken at the source.

MANAGEMENT IMPLICATIONS

In headward drainage basins, appropriate diagnosis of land surface condition, and actions to ensure soil and landscape stability and ecosystem integrity, should be focused upon hillslope stability and drainage formation. Land-use activities should be designed to minimize changes to hydrological pathways on slopes, and to avoid incremental slope instability and disturbance of the natural channels. Hydrological watershed assessment and slope stability assessments are the appropriate tools to achieve these objectives in relatively small, upland drainage basins with a high proportion of slope-coupled channels.

Downstream—in reaches with valley flats or floodplains—appropriate diagnosis of water-related problems must be focused on the stream channel and riparian zone. Channel bank condition is the key to overall channel stability once sediments are reduced to sizes that are relatively frequently mobilized (i.e., mobilized by frequently recurring flows) (Millar 1999). Appropriate land management should be concentrated on maintaining the natural rate of sediment transfer along stream channels. The most important action is the maintenance of streambank integrity. An implication of these requirements is that in larger drainage systems the major management tool for uncoupled channels downstream should be stream channel stability assessment.

These management requirements lead to recommendations loosely based on drainage basin size because of the characteristic association of certain topographies and certain processes with limited ranges of drainage area, and because of the hierarchical nature of drainage networks. For example, drainage basins of order 1 km^2 area will nearly always exhibit headward channel characteristics. Channel characteristics are determined by hillslope processes unless they are wetland type headwaters within upland valleys, on

plateaus, or in extensive bottomlands. Watershed assessment procedures are most appropriate, and gully assessment will often be required. Channel assessment is not worthwhile. In wetlands, interruptions of drainage associated with roads (which may become dams) require special attention.

At order 10 km^2, a drainage basin may have a limited valley-bottom reach of low (<1%) or moderate (<4%) gradient. These channels still experience highly variable flows. There may be considerable valley-bottom sediment storage, and channels may be only partially coupled to adjacent hillsides. Channels at this scale are most sensitive to increased upland production of sediment because a substantial portion of it is delivered to these channels and comes to rest there. Transient episodes of aggradation and degradation are most severe there. The channels exhibit great structural complexity. These are often the headmost channels occupied by significant fish populations. Woody debris jams are often effective in diverting flows and intercepting sediments. Both watershed and channel assessments will ordinarily be required.

At order 100 km^2, channels usually exhibit valley flats and uncoupled stream channels in their downstream ("distal") portions. Flows are strongly modulated seasonally, but are less variable than in headwaters. At this scale and in larger basins, sediment dispersive effects (which, for channel bed-forming material, are very strong because of the limited mobility) condition episodes of sediment aggradation and degradation to be persistent, but of only moderate intensity. The chance to identify the individual sediment sources that create these trends becomes severely limited in basins larger than a few hundred square kilometres. Channel assessment procedures are appropriate, but, because of the long time scale for sediment dispersion, integrated watershed assessments will rarely be useful at drainage scales beyond 30 km^2 or so. Of course, assessments will still be conducted in many of the individual tributaries.

Because of topographic variability, however, decisions about appropriate watershed diagnostic procedures must be taken on a watershed-by-watershed basis. For example, many streams in both plateaus and mountains may have low-gradient headwaters (within hanging valleys in the mountains) with steeper gradients downstream where the channel descends toward the main valley. In the gorge, steep sideslopes may be directly coupled to the channel and it is here that slope stability assessments are most critical. Channel assessments may be applicable along the headwater stream if it is fish-bearing, but no assessment may be necessary if the channel downstream is steep and rocky, with fish barriers. Many valley-bottom streams have extended "partially coupled" reaches where the stream undercuts steep bluffs or is confined against steep, unstable banks by tributary alluvial fans. The floodplain is discontinuous. Appropriate methods for assessing the state of such channels and their contributory watersheds need to be selected in light of these conditions. For the same reason, the diagnostic exercise is best conducted as an investigation of the actual land condition, and hydrological regime and patterns of sedimentation as well. This is an expert process.

In comparison, when expert experience is lacking, index assessments serve a useful function to direct attention systematically toward frequently critical conditions. In the long run, however, they form a poor basis for continuing land management. Index assessments are based upon observed statistical associations of conditions and events. In view of statistical variance, certain proportions of judgements are bound to be wrong. Thus, outcomes are asymmetric. A successful land management decision preserves land and soil resources, water quality, and ecosystem structure for future use and further decisions. On the other hand, a decision based on a misleading outcome may foreclose that option for a more or less protracted period when soil or channel degradation follow. As land use continues, the cumulative effect of poor decisions degrades the overall land resource. Depending upon how conservative the decision system is (which will depend upon the perceived profitability of resources), this asymmetry will become evident more or less quickly. As long as there is pressure to increase resource production, the problem will remain unless actual land management is based more directly upon analysis and understanding of physical conditions and processes. Progress in this direction is the objective of this workshop.

SUMMARY

The factors that govern morphology and processes along stream channels are the amount and timing of water delivery to the channel, the amount and calibre of sediment delivered, the gradient over which the channel flows, and the conditions of bank vegetation and wood supply to the channel. In the interior of British Columbia, watershed processes are forced by water inputs resulting from summer convectional storms, larger-scale frontal precipitation, snowmelt, and rain-on-snow. Each of these sources is more or less seasonal in character. In the long run, the greatest runoff results from large storms and from rain-on-snow, since these can deliver the greatest volumes of water to the surface over a period that persists for longer than the time of runoff formation.

For land-management purposes, a fundamental distinction must be recognized between low-order, headwater drainage basins and larger, higher-order ones. Headward basins are the source of channelled streamflow and of much of the sediment—inorganic and organic—that moves through the drainage system. Trunk streams combine drainage from many headward channels. The former are often characterized by relatively steep slopes that are coupled directly to stream channels; the latter include trunk stream channels that are buffered from adjacent slopes by a valley flat, which is often a floodplain.

Coupled channels receive sediment inputs directly from adjacent slopes and headward hollows. Therefore they are subject to episodic major disturbance, usually in the form of landsliding. Meteorological forcing of such events is relatively rare at any particular place in the landscape, though it is frequent regionally. Events able to evacuate substantial volumes of the larger material that lands in the channel are even more rare. Consequently, headward basins export sediment in the long run, but, in the short run, substantial accumulations may occur along steep channels. Accumulation may occur over periods varying from years to centuries, but much of it may be released during a single extreme event. Sediment movement down steep channels often occurs as debris flows. Much of this material comes to rest on debris cones, but the finer part moves into the valley bottom where it may be stored for more or less extended periods in alluvial fans and floodplains.

Trunk channels experience the integrated effect of episodic disturbance at many places in the headwaters. Sediment delivery and significant onward transfer occur frequently in such channels, but the relative severity of individual events is attenuated by the dispersive effects of increasing travel distance from source (of both water and sediment). The proximal (upstream) valley reaches, closest to the sediment sources, represent the most sensitive part of the drainage system, for sedimentation trends here can be abruptly altered, depending on the pattern of sediment delivery. Sediment is remobilized from channel bars and stream banks during normal snowmelt and rainstorm floods, leading to continually changing channel morphology. On larger rivers, it is difficult to determine the ultimate source of transient instability, which may persist at modest intensity for many years or decades.

Exceptions occur. Headwater channels on the plateaus may be flat and may drain extensive wetlands. In the mountains, similar headwaters sometimes occur in hanging valleys. Conversely, many valley streams are incised into, and are at least partially confined by, high banks composed of Pleistocene sediments that represent additional sediment sources.

Appropriate diagnosis of land surface condition and actions to ensure soil and landscape stability and ecosystem integrity should be focused upon hillslope stability in headward drainage basins. Land-use activities should be designed to minimize changes to hydrological pathways on slopes, and to avoid incremental slope instability and sediment delivery to stream channels. Along valleys, the focus of attention must be the stream channel and riparian zone. Appropriate land management should concentrate on maintaining the natural rate of sediment transfer along stream channels. The most important action is the maintenance of streambank integrity, for this controls overall channel stability. An implication of these requirements is that hydrological watershed assessment is an appropriate management tool in relatively small, upland drainage basins with a high proportion of slope-coupled stream channels, but that in larger drainage systems the major management tool for uncoupled channels should be stream channel stability assessment. Because the character of individual reaches may vary from the dominant pattern—with low-gradient headwater reaches and confined reaches along trunk valleys—the actual choice of diagnostic tools and management prescriptions should be made on a reach-by-reach basis.

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Overview of the Development of IWAP from Point Scores to Freeform Analysis

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ABSTRACT

The Interior Watershed Assessment Procedure (IWAP) is an assessment of the cumulative impacts on a watershed from past forest harvesting practices. The current methodology (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) is only one of many possible methods of assessing watersheds. This paper reviews other approaches to watershed assessment, discusses the history of watershed assessment methods in British Columbia, describes the rationale for selecting the current approach, and makes some predictions about the future of the art of watershed assessment.

INTRODUCTION

The first attempts at watershed assessment in British Columbia began in the late 1970s, soon after clearcutting became established as the dominant silvicultural system in the province. Over the ensuing 20 years a number of methods for watershed assessment have been tried. Evaluating the present and potential future impacts of extensive forest harvesting on aquatic resources is a very complex task. A challenge in all jurisdictions where watershed analysis has been used is to balance the task of trying to understand the complex processes in the watershed versus the practical need to conduct these analyses in a timely and cost-efficient manner. This dilemma is particularly relevant in British Columbia, where 10 000 new cutblocks are harvested annually and forest harvest activities are taking place in hundreds of watersheds in any one year. This paper reviews the history of watershed assessment in the province and attempts to explain how we arrived at IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999).

WATERSHED ASSESSMENT MODELS

There are at least seven types of watershed assessment models that have been tried in British Columbia, four as operational tools and three within a research context. The seven models, with an example for each, are listed in Table 1, and a brief description of each type follows.

TABLE 1 *Types of watershed assessment models*

Types	**Examples**
Critical thresholds	Okanagan Guidelines
Expert systems	Coastal Watershed Workbook
Process models	DHSVM
Empirical models	FIPS
Indicator models	IWAP 1
Professional assessments	IWAP 2
Integrated landscape unit assessments	no examples available

Critical Thresholds

The "critical threshold" method is setting "a percentage of watershed cut" restriction on the amount of harvesting that can take place in a watershed over a set period of time. One of the first attempts at regulating harvest rates for hydrological values was described in *Watershed Management Considerations for Operational Planning in TFL 39, Graham Island* (Toews and Wilford 1978). The authors recommended "distributing harvest and restricting the rate of cut to 33% of a watershed in 25 years." Twelve years later, the Okanagan Guidelines (B.C. Ministry of Forests 1992) specified critical limits of a "maximum of 30% of a watershed harvested since 1965" and a "maximum of 20% of a community watershed since 1965."

Slightly more sophisticated examples are establishing Equivalent Clearcut Area (ECA) limits. The ECA method establishes a threshold of a certain percentage of the watershed in a clearcut condition, but gives credits for second growth, thus allowing more harvest over time. Prior to 1995, a number of watersheds in British Columbia had total clearcut area limits of 30% of the watershed.

Critical threshold models are attractive to forest planners because they are simple and can be incorporated into timber supply and planning models. The method assumes, however, that all watersheds are hydrologically similar. As rates of harvest approached these limits in most watersheds, there was a desire to develop methods that were more tailored to individual watershed characteristics. Hydrologists also expressed concern that these methods were essentially concerned with peak flows as the primary focus and gave no consideration to riparian, landslide, or channel instability impacts.

Process Model

Process Models are computer simulation models that are based on a theoretical understanding of watershed processes, which are described in equations and used to simulate water flow and sediment production over time. The Distributed Hydrological Soil Vegetation Model (DHSVM) described by Whitaker et al. (2001) is the best example of a hydrological process model.

Distributed process models take into account the distribution of topography, soil, vegetation, and climate characteristics across the watershed by characterizing the watershed by pixels or polygons. These models have large data requirements and long calibration periods, which make them very expensive. The DHSVM model for Redfish Creek, for example, cost in excess of $60 000. The models work well for flow simulation, but usually do not model other watershed processes.

Process models are best as research or validation tools—for example, DHSVM was used by Whitaker et al. to test the Peak Flow Index (this publication). They are impractical for routine watershed assessment purposes in their present configuration.

Empirical Models

A second group of models is empirical models, where watershed processes are estimated from empirical correlation with observations. One example of this is the Fish/Forestry Interaction Model (FFIPS) (Marmorek et al. 1998), which attempts to model mass wasting, and changes in riparian, stream channel, and fish habitat in coastal watersheds.

An example from the FFIPS model (Figure 1) shows large woody debris (LWD) volume in the watershed declining over a 125-year period, but total sediment storage rising. Estimating the number of landslides that contain large trees and that enter a stream each year produces the graph. The numbers are not physically based, but are derived from general correlations observed in the watershed

Empirical models are best suited for strategic planning or research purposes. They are also useful for understanding the sensitivity of different processes or for looking at long-term trends.

Expert System

An expert system method uses the collective knowledge of a group of experts to determine the numerical thresholds for ranking indicators of watershed sensitivity. An example of this approach is the *Watershed Workbook: Forest Hydrology Sensitivity Analysis for Coastal Watersheds* (Wilford 1987).

The workbook asks 12 questions about the watershed. Each possible answer was previously ranked from –3 to +3, based on "expert opinion" and then the 12 answers were rolled up for an overall watershed sensitivity rating. The algorithms behind the system were not process-based and are not transparent but were "black box." The final answer was intended only as a "red flag" to trigger more detailed analysis.

The Watershed Workbook method was eventually abandoned for a number of reasons. It was intended as a filter to identify watersheds where more detailed investigation was needed, but the filter was too coarse, and resulted in most watersheds with a significant amount of prior harvest being identified. Because the algorithms were "black box" there was no useful information coming from the analysis that could be used in the more detailed investigation. Finally, the analysis was not useful for solving problems because the descriptive data were hidden.

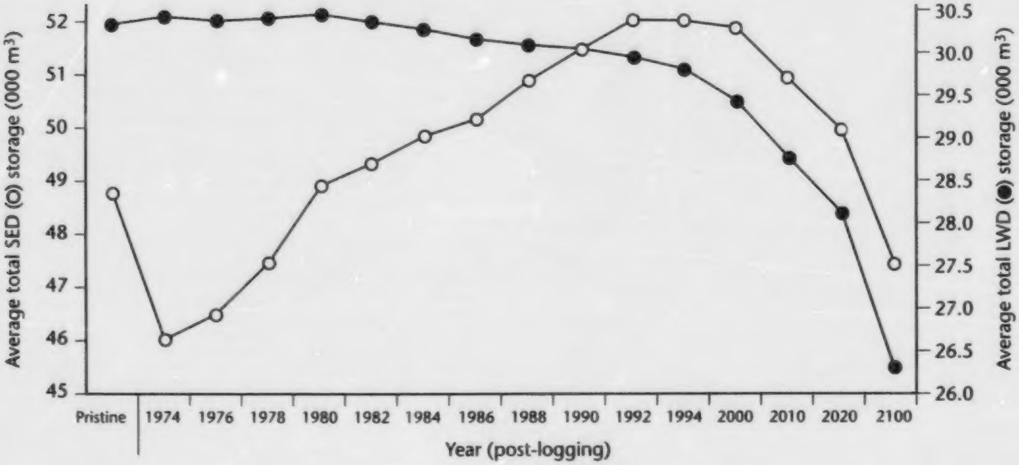

FIGURE 1 *Modelling the change in sediment storage (SED) and large woody debris (LWD) storage over time in Carnation Creek (from the FFIPS model).*

Indicator Models —IWAP 1

Indicator models use point scores of measured watershed characteristics or land-use patterns to score the overall watershed health or impact of harvesting on the watershed. The original IWAP Level 1 analysis is an example of an indicator model (B.C. Ministry of Forests and B.C. Ministry of Environment 1995).

IWAP 1 (B.C. Ministry of Forests and B.C. Ministry of Environment 1995) was introduced with the *Forest Practices Code of British Columbia Act*, which provided the first legal requirement for conducting watershed assessments in British Columbia. All of the province's 475 community watersheds, and certain watersheds designated as high-value fishery watersheds, were required to have watershed assessments completed within 3 years.

It was realized that there were insufficient professional resources experienced in watershed assessment to complete hundreds of watersheds in such a short time period. We also realized that a large percentage of these watersheds may not have any significant problems, and so professional resources were best directed at those that did have problems. Therefore, a filter approach was adopted.

The 1995 version of IWAP was a three-level filter system:

Level 1: An office-based reconnaissance overview of the watershed based on indicators of watershed impact
Level 2: A channel stability assessment, triggered by a moderate or high Level 1 score
Level 3 A detailed field assessment of mass wasting, erosion, riparian condition, and stream channel stability, triggered by a moderate or high score in Level 2.

Level 1 IWAP was designed as an indicator system that could be completed by a forest technician with basic map and airphoto skills. It was based on GIS measurements of watershed attributes that were considered proxies for watershed health. The questions were grouped into "hazard indices" for peak flow, sediment, landslides, and riparian condition. Each hazard group had two to four basic measurements (such as length of road on unstable slopes), which were individually scored and then rolled up to produce a hazard score for each hazard (Table 2).

The scoring for the individual measurements as well as the algorithm for rolling up the scores into a hazard score was done through look-up matrices and algorithms. The algorithms and scores were designed by experienced hydrologists working with results from 20 watersheds that were either research watersheds or were well known because of detailed field assessments in the past.

TABLE 2 *The indicators and scoring key for the mass wasting hazard group in IWAP 1 (B.C. Ministry of Forests and B.C. Ministry of Environment 1995).*

		Score					
Impact category	**Indicators**	**0**	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**
Mass wasting	11. Landslides (no./km²)	0	0.04	0.08	0.14	0.24	>0.4
	12. Roads on unstable slopes (km/km²)	0	0.06	0.12	0.20	0.30	>0.4
	13. Streambanks logged on slopes >60% (km/km²)	0	0.06	0.12	0.20	0.30	>0.4

The Level 1 resulted in scores for the hazards of peak flow, sediment, landslides and riparian condition. If the score for suspended sediment was more than 0.5 then a sediment source survey was triggered. If any of the other hazards was more than 0.5 then a Level 2 channel assessment was triggered. No attempt was made to "roll up" the individual scores into an overall watershed score. In an attempt to address cumulative affects, matrices were produced that paired one hazard score against another.

The Kootenay-Boundary Land Use Plan (Kootenay Inter-Agency Management Committee 1997) also adopted the Level 1 indicator system for domestic watersheds. Adopting a smaller list of four critical indicators (Table 3), the method allowed an overview assessment of 2000 domestic watersheds in a short period of time.

The Level 1 method was successful in analyzing a large number of watersheds over a 1-year time period. A compilation of the IWAP Level 1 results from 1400 sub-basins (Carver and Teti 1998) examined whether the results appeared reasonable based on the distribution of scores and average hazard levels. The authors found that there was a good distribution of hazard scores from 0 to 1.0, but there was some skew. Surface erosion hazard was usually high, and riparian hazard was also often high. They were unable to determine whether this was due to actual hazard levels or whether the scoring system needed adjustment. Looking at average individual hazard scores for all IWAPs (Figure 2), Carver and Teti found that the means ranged from 0.2 (landslides) to 0.55 (surface erosion). A Level 2 analysis was triggered in about 50% of the watersheds. In conclusion, the distribution of scores and hazard levels was found to be reasonable and was conservatively segregating watersheds into the desired groups. Furthermore, the chance of a Type II error—passing a watershed when there was actually a problem—was considered low.

Level 1 IWAP had a number of strengths as a watershed assessment tool. It was a consistent repeatable method—no matter who did the analysis, the same result was recorded. It provided a logical filtering of watersheds into no-problem/possible-problem groups. Hundreds of watersheds were analyzed in a year, which would not have been possible using field-based methods. Professional resources were saved for those watersheds that potentially had problems, rather then spending time in watersheds with no potential problems. The analysis was very inexpensive, particularly for those Licensees with good GIS capability. As hundreds of watershed were completed, it gave a useful regional picture, allowing between-watershed comparisons of hazards to be made in order to prioritize watersheds. Finally, the method was very easy to audit, because the results were quantitative and repeatable.

TABLE 3 *Indicators for watershed risk in domestic watersheds in the Kootenay-Boundary Land Use Plan (Kootenay Inter-Agency Management Committee 1997)*

Indicator	Low	Moderate	High
Equivalent clearcut area (ECA)	<0.3	0.3 to 0.4	>0.4
Road density (km/km^2)	<1.5	1.5 to 2.1	>2.1
Stream crossings (no./km^2)	<0.4	0.4 to 0.6	>0.6
Roads on unstable slopes (km/km^2)	<0.15	0.15 to 0.30	>0.3

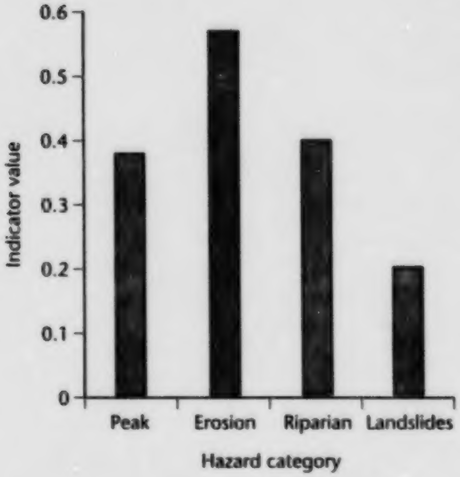

FIGURE 2 *Average values of IWAP Level 1 scores, by hazard group (after Carver and Teti 1998).*

Unfortunately, there were also problems with the Level 1 IWAP. The IWAP 1 was constructed as a three-part system, where Level 1 triggered field assessments; but in most cases only a Level 1 was completed and watershed recommendations were made from that analysis alone. It was found that the "process" of plan referral after each stage of the three-part IWAP took too long to complete and industry wanted a more efficient process with a single set of referral comments. The intent of the hazard scores was a "red flag" system, but instead the scores became goals, such that no development was permitted that resulted in a score greater than 0.5. The IWAP 1 Guidebook recommends that the process be guided by an interagency "round table," but this was not common. Recurring Recommendations on the Forest Development Plan were repeatedly omitted from the IWAP 1 reports. When Forest Development Plan recommendations were made they were often identical to the "interactive matrices" in the IWAP 1 Guidebook that were intended only as examples. Many professionals doing follow-up fieldwork found numerous instances where false positives occurred. Finally, it was felt that the scores were too generic, and if the system was to be retained then regional variability must be taken into account.

Other criticisms of the IWAP 1 process came from the Watershed Restoration Program (WRP). While not initially intended for restoration program purposes, the IWAP had been adopted by WRP for prioritizing watershed restoration. However, it lacked the needed detail for this type of use, and most WRP planners did not find IWAP 1 to be a useful tool.

In summary, the IWAP 1 procedure has been very useful for the initial sorting of watersheds, and for implementing an assessment procedure in a very short period of time. However, as familiarity with the watersheds grew, there was a desire for a single integrative procedure that provided a depth of information for proper resource management.

Professional Assessments—IWAP 2

As a result of the problems with the implementation of IWAP 1, a new IWAP procedure was introduced in 1999. A professional assessment was required in all watersheds following the structure described in the IWAP Guidebook

(B.C. Ministry of Forests and B.C. Ministry of Environment 1999). Mandatory components of the new procedure were:

- A Watershed Advisory Committee to review the results of the assessment and make recommendations must be established.
- The assessment must be completed by a qualified professional.
- Field work must be done.
- A Watershed Report Card, which parallels the data inputs into IWAP Level 1, must be completed.
- Recommendations must be made to direct the forest development plan.

There are numerous advantages to the new procedure. The information gathered and the assessment made is more reliable because it is conducted by a professional and is unique to that watershed. Similarly, the recommendations are germane to that specific watershed. The process is not iterative, but instead a single product with final recommendations is produced.

There are, however, some problems with the new procedure as well. Unlike IWAP 1, it is very difficult to audit the results. There are few controls, so the potential for bias exists. Likewise, it is difficult to compare the results between watersheds for regional priority setting. IWAP 2 is significantly more expensive compared to IWAP 1, but not if all three levels of IWAP are completed. The expense is particularly high for "no-problem" watersheds because they still require professional assessment. Finally, there has been some problem in finding enough qualified professionals, but this has not been as significant as envisaged.

A limited amount of quality assurance of IWAP 2 reports has been carried out to date. The recommended methods described in the guidebook are largely followed and there is an overall consistent approach and consistent amount of field time between professionals. The exception to this is the stream channel stability component, where method and amount of detail collected in the field differ significantly. Within any watershed there is consistent information collected and sensitivity assessments generally appear consistent. The emphasis placed on the peak flow hazard varies from professional to professional. The role of the Watershed Advisory Committee differs widely. In isolated watersheds it appears that the Committee just rubber-stamps the professional assessment; in other watersheds the Committee takes a more active role.

Integrated Landscape Unit Plans—The Future of WAPs

It is risky to predict the future, but the next stage for watershed assessment will probably be some type of integrated landscape unit plan. Landscape Unit Plans that integrate watershed assessment, riparian assessment, and biodiversity objectives are now being considered in a Code Pilot Area project. The watershed will be zoned into management polygons, and objectives will be set for each management unit. As well as meeting objectives for that unit, the overall landscape unit or watershed objectives would also have to be met. The first pilot of this approach is being developed for an Okanagan watershed over the next two years.

SUMMARY

This paper demonstrates that the art of watershed assessment is an evolving one. Watershed Assessment in British Columbia has evolved from threshold methods (1980s) to expert systems (1986), to indicators (1995), to professional assessment (1999). Research contributions to watershed assessment have come from process and empirical models that test the sensitivity of different factors and examine long-term trends. The papers that follow in these proceedings examine many of the assumptions currently made in watershed assessment and will contribute to the continued evolution of the procedure.

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Using Indicators to Assess Hydrologic Risk

MARTIN CARVER

ABSTRACT

In British Columbia, forest managers employ indicators for evaluating hydrologic constraints. Although the Watershed Assessment Procedures provide the most visible example of this, broader administrative levels such as Land and Resource Management Plans and Timber Supply Reviews also make use of hydrologic indicators to support decisions. Unfortunately, the way indicators are used often does not take full advantage of current knowledge, nor does it always support transparent decision-making with scientific information clearly separated from social values. This paper reviews British Columbia's use of hydrologic indicators and provides practical options for improving the quality of hydrologic information provided to decision-makers.

In assessing forest-management options, decision-makers require clear expression of possible hydrologic outcomes. How these outcomes are best presented for consideration in decision-making is influenced by the spatial scale under consideration, data availability at this scale, data quality, analytic capabilities, and the current level of scientific knowledge. The literature demonstrates the prevalence of indicator and process models. The present version of the Watershed Assessment Procedure has moved away from a reliance on indicators to a greater focus on professional opinion based on limited field work. This shift may be suitable at the scale of specific watersheds, but it does not address broader management planning scales. The use of Equivalent Clearcut Area as a single indicator of hydrologic impact continues to be evident in British Columbia at all management levels despite knowledge that Equivalent Clearcut Area can be only weakly linked to hydrologic impact.

A host of challenges is preventing the effective use of indicators in hydrologic assessment in British Columbia. The uncertainty and complexity associated with hydrologic linkage mechanisms present real challenges to the applied scientist when attempting to articulate potential hydrologic outcomes to decision-makers. Data availability/quality and computational power continue to be significant modelling issues. Evaluation of results and of the procedure itself have been lacking in British Columbia and yet form a cornerstone of effective adaptive management.

It is suggested that a preferred approach for supporting broad management decisions is a risk-assessment framework that provides a clear separation between scientific interpretation and value-based choices. A systematic evaluation of indicators linked to applied research would be required, along with standardized measures of hydrologic impact. It is concluded that until reliable process models can be developed and detailed data are available on

a broad basis, indicators will continue to be an essential basis for making forest-management decisions.

1 INTRODUCTION

Hydrologic information is vital to forest management over a wide range of spatial scales: site-specific operational concerns (culvert installations, bridge crossings, drainage requirements at seepage sites, etc.), assessments of small watersheds (<5 km^2), planning for medium and large watersheds (5–500, and >500 km^2), and strategic planning at regional (e.g., Land and Resource Management Plans or Timber Supply Reviews) and provincial scales. The tools available for considering hydrologic constraints vary with scale:

- Under 5 km^2 (site and small watershed): Assessment involves professional consideration of site-specific issues (not addressed here).
- 5–500 km^2 (medium watershed): Watershed Assessment Procedure (WAP).
- Over 500 km^2 (large watershed, regional, provincial): Few tools available; sub-watershed WAP application.

In its initial version, the WAP contained an initial Level 1 screening filter developed as a mapping exercise (B.C. Ministry of Forest and B.C. Ministry of Environment 1995). Due to problems in its application, this office-based screening approach was abandoned. The current version of the WAP is best suited for medium-sized watersheds and requires field work (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). Recommendations are provided by an experienced professional based on map work (including indicators) and field work. This approach appears successful for the 5–500 km^2 spatial scale. Due to the new requirement for field work, it is problematic to apply the WAP over larger scales. At larger scales, assessment is generally for strategic planning and necessarily excludes field work. Currently, few tools are available at these scales. Crude assumptions tend to be made—often in relation to Equivalent Clearcut Area (ECA)—to yield planning limits. It is widely recognized that the assumptions are weakly correlated to hydrologic impact (see Carver and Utzig 2000); however, in the absence of other tools, this approach persists.

In an effort to identify patterns in forest development, Carver and Teti (1998) presented a descriptive summary of WAP (Level 1) results. They found a high degree of variability both in terms of (natural) site factors and the application of management across British Columbia and across forest regions. They also noted that no single indicator correlated well on its own to hydrologic impact.

A study was commissioned by the Arrow Forest District to develop a hydrologic risk-assessment framework for use in broad-scale planning (Carver and Utzig 2000). The approach given in the present paper is based on the work provided in that earlier study. Indicators form a focus in this framework because of the need for an office-based assessment. Although the work was specifically developed in the Nelson Forest Region, the concepts and framework are applicable across British Columbia.

1.1 Objectives

There are three objectives of this paper:

1. Review available approaches to assessing hydrologic risks (at strategic planning scales).
2. Explain benefits and identify challenges to using indicators in forest-development planning.
3. Propose a framework for addressing hydrologic constraints in broad-scale planning.

2 MODELLING APPROACH

The modelling approach presented in this paper is described below, including the risk-assessment framework and a summary of the site and management factors considered.

2.1 Risk-assessment Framework

Figure 1 illustrates a general approach to risk assessment where environmental values are of concern (adapted from B.C. Ministry of Environment, Lands and Parks 2000). The approach involves selecting and characterizing environmental values of interest (in this case water, aquatic habitat, and riparian values), and characterizing management regimes that create pressures that in turn affect the environmental values.

Indicators are used as a surrogate measure of the changes in risk associated with pressures interacting on the chosen environmental values. The interactions between management and the environmental values are modelled

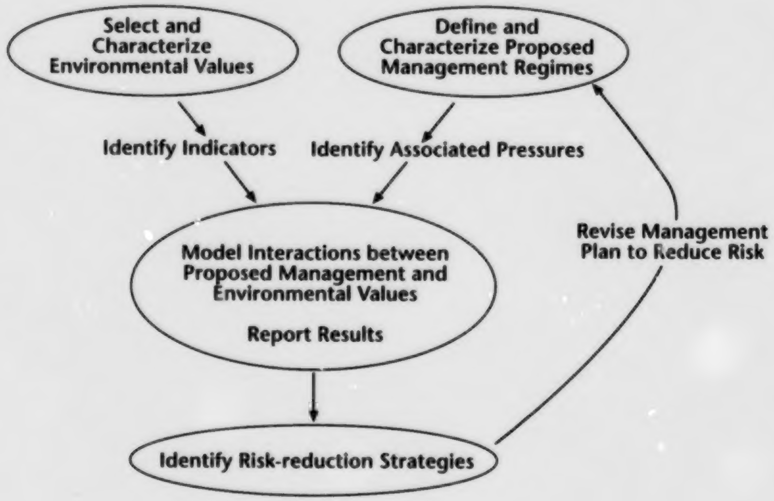
Select and Characterize Environmental Values
Define and Characterize Proposed Management Regimes
Identify Indicators
Identify Associated Pressures
Model Interactions between Proposed Management and Environmental Values
Report Results
Revise Management Plan to Reduce Risk
Identify Risk-reduction Strategies

FIGURE 1 *Illustration of the general risk-assessment framework used in environmental assessment.*

based on current knowledge. Cause-and-effect mechanisms identified during the assessment may suggest risk-reduction strategies for consideration by forest managers.

Risk can be defined variously. Here, hydrologic risk is defined as the probability of an adverse outcome (e.g., increased sedimentation, flooding). The word "hazard" is sometimes used synonymously with this concept of risk. In this paper, the term hazard will be used to suggest the potential, on a local or site basis, for an event to occur that could contribute to a deterioration in an environmental value (e.g., landslide hazard). A hydrologic indicator is defined as a parameter that can be measured, observed, or derived, and that provides a pattern or trend in aspects of a hydrologic regime (aquatic environment) of a watershed.

2.2 Modelling Factors

The physical basis of any model must include consideration of both site and management factors. In the present application, environmental values of interest are those resources associated with the aquatic environment and potentially affected by the management activities under consideration—water quality, quantity, and timing, aquatic habitat, and property in affected areas. Four hydrologic outcomes are identified that can affect these values: increased peak flows, reduced low flows, increased suspended sediment, and channel destabilization.

2.2.1 Site factors A wide range of watershed characteristics act and interact to produce background hydrologic hazards. Table 1 presents a summary of many of the site factors of concern in terms of their effect on causing the four hydrologic outcomes: peak flow increase, low-flow decrease, sedimentation, and channel instability.

TABLE 1 *Watershed characteristics that shape background hydrologic hazard*

Flow hazards	Sediment hazards

Peak-flow regime
• Extent of natural forest cover (ECA buffers)
• Soil moisture storage
• Low-elevation lakes/wetlands (flow buffers)
• Fire disturbance
• Basin morphology
  • elevational distribution
  • aspect/elevation complexity
  • drainage density
  • basin size and shape
• Climatic influences
  • precipitation amount/distribution (rain/snow)
  • intensity/duration/frequency of storm events
	Sediment regime
	• Terrain instability (bedload)
	• Soil erodibility (suspended load)
	• Channel stability (see below)
	• Fire disturbance
	• Glaciers
	• Low-elevation sediment traps (e.g., lakes)

Low-flow regime • Glaciers and long-duration snow fields • Wetlands, high-elevation lakes • Subsurface water storage • Elevational distribution • Precipitation amount/distribution (rain/snow)	**Channel stability** • Channel type • Peak-flow regime (see left) • Fire disturbance • Flood disturbance • Low-elevation sediment traps (e.g., lakes) • Terrain instability

2.2.2 Management factors and process linkages Figure 2 illustrates the way in which the two primary management activities—forest harvest and road-building—may bring about (negative) hydrologic outcomes that can affect the aquatic values of concern. This flowchart emphasizes the multiple outcomes possible from forest management. There is general agreement in the scientific community that these management linkages exist as indicated here (e.g., see Church 1996); however, disagreement is likely regarding their magnitude and importance given a specific landscape and under a specific management regime.

Many of these processes indicated here occur simultaneously and, as a result, their individual outcomes can be obscured or even mitigated by other processes. For example, although increased rates of snowmelt combined with drainage diversions and flow interception can reduce water availability for late-season low flows, studies show that these effects are generally offset by the increased water availability due to increased snow accumulation and lowered transpiration (see Johnson 1998) resulting in *increases* in late-season low flows after forest harvest and road-building (assuming that de-watering does not occur due to high sediment inputs). In this case, these compensating factors are not persistent; and it has also been shown that after some years of forest regrowth, low flows can decline to below pre-logging levels (e.g., Keppeler and Ziemer 1990). These temporal changes in resource impact should be considered in the scoring of any proposed rating system.

Figure 2 identifies six processes:

Cut/fill and soil exposure Roads increase sediment production through waterborne erosion and mass wasting. Active surfaces of forest roads and skid trails represent exposed areas where sediment is produced due to abrasion, rilling, and in some cases, gully erosion. These effects can be mitigated with

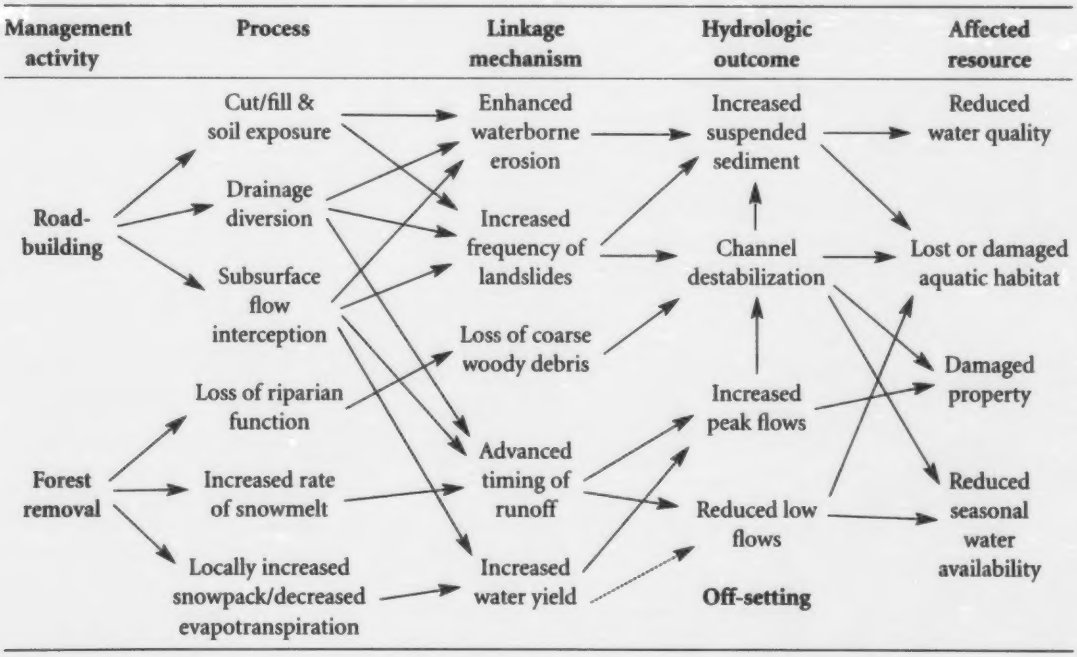
Management activity
Process
Linkage mechanism
Hydrologic outcome
Affected resource
Road-building
Forest removal
Cut/fill & soil exposure
Drainage diversion
Subsurface flow interception
Loss of riparian function
Increased rate of snowmelt
Locally increased snowpack/decreased evapotranspiration
Enhanced waterborne erosion
Increased frequency of landslides
Loss of coarse woody debris
Advanced timing of runoff
Increased water yield
Increased suspended sediment
Channel destabilization
Increased peak flows
Reduced low flows
Off-setting
Reduced water quality
Lost or damaged aquatic habitat
Damaged property
Reduced seasonal water availability

FIGURE 2 *A flow chart illustrating the linkage between forest development and hydrologic impacts.*

surface materials, road deactivation, revegetation, and disuse. Mass wasting can result directly from road construction—for instance, where a fillslope fails. Cutbanks can be undermined and have the potential to cause chronic sediment sources contributing directly to ditch lines. Enhanced production of fine sediment increases suspended sediment concentrations, especially during significant freshet rain-on-snow events. Enhanced delivery of coarse sediment to streams can destabilize channels, resulting in, among other outcomes, a further increase in recruitment of fine sediment due to streambank erosion.

Drainage diversion The drainage system associated with the road network can significantly modify the natural drainage pattern. Water can be routed to drainage features and hillslopes that otherwise would not experience the flow. These new flows can initiate landslides or gullying, delivering sediment to streams. In addition, diverted drainage can advance the timing of runoff, thereby increasing peak flows and potentially decreasing late-season low flows.

Subsurface flow interception Roads can bring subsurface flows to the surface, routing them to the drainage network. In addition, the road network acts as an extension to the drainage network, efficiently routing runoff to the natural drainage network (Wemple et al. 1996). Both of these processes have the effect of advancing the timing of runoff and serving to potentially increase peak flows and decrease late-season low flows. However, in the low-flow case, there may be compensation of these effects resulting from diminished transpiration losses. In any case, this mechanism is most likely to occur when roads pass through wet sites and/or require deep cuts (slopes with gradient over 40%).

Loss of riparian function Harvesting in the riparian zone may reduce bank stability through direct disturbance and loss of root strength. Harvesting in the riparian zone may remove sources of coarse woody debris that may be necessary for channel stability. Other effects such as increased temperature due to the removal of the riparian vegetation are not considered in this analysis.

Increased rate of snowmelt Openings in the forest (due to harvesting and roads) increase the melt rate of the snowpack through greater exposure to solar radiation. Very small openings and partial cutting areas may experience an intermediate melt rate in relation to extensive clearcut areas. Similar to the effect of flow interception, a faster melt rate has the potential to increase peak flows and decrease late-season low flows, depending on the aspect and elevation of the openings. Note, however, that other processes occurring simultaneously may adjust the (net) outcome significantly. For example, although increased snow accumulation (see next point) can enhance the effect of increased melt rates on peak flows (i.e., make them higher), decreased evapotranspiration can diminish or often reverse the effect of melt rate on low flows where extensive openings are created through forest harvest (see Johnson 1998).

Increased snowpack and decreased evapotranspiration Openings in the forest—whether due to harvesting or to roads—generally increase winter snow accumulation through the loss of canopy snow interception and sublimation. The enhanced snow pack results in higher total basin runoff, which in turn can increase peak flows. The effect of harvesting is temporary—as the trees grow and canopy closure occurs, hydrologic recovery takes place, resulting in a gradually diminishing effect. In contrast, the effect of roads is permanent unless site rehabilitation/revegetation is accomplished. In general, enhanced snowpacks increase low flows, but it is suspected that 5–10 years after initial harvest, depending on the type of new vegetation, reduced low flows can occur if water-uptake behaviour has changed. Increased flows also result from decreased evapotranspiration.

Small openings (less than five tree heights in diameter) can yield a snowpack different from that of large openings due to wind effects, and in some colder climates, sublimation from the ground. Given moderate wind and temperature regimes, the snowpack within small openings (one to five tree heights in diameter) is roughly equivalent to that of large openings.[1] In combination with the intermediate melt rate of small openings, it is generally expected that openings under five tree heights in diameter result, overall, in a potential for affecting peak flows. This effect is intermediate between full canopy closure and large openings. The snowpack in very small openings (less than one tree height in diameter) may differ from that of small/large openings due to the higher relative significance of edge effects. Note that the effect of enhanced snowpack can be mitigated by the use of single-tree selection. Extremely large openings can result in a reduced snowpack if wind scour is significant.

These hydrologic outcomes cause resource impacts, as shown in Figure 2. Reduced low flows have been observed only rarely, and they affect mainly water quantity for consumption/irrigation and fish habitat (greater documentation exists of increased low flows). In contrast, increased peak flows can affect property directly through flooding, and they can also indirectly affect domestic water quality and fish habitat through channel destabilization. The degree to which these effects occur as a result of management will vary depending on the relative intensity, duration, and extent of the impacts resulting from the forest-management regime applied.

2.3 Indicators

2.3.1 Strengths The strengths of environmental indicators include their flexibility, low cost, and general simplicity and ease of application (e.g., Westland Resource Group 1995 and Canadian Council of Forest Ministers 1997).

Flexibility A variety of indicators is available, both in the form of directly measurable quantitative data and indirect qualitative evaluations of related factors. New tools are becoming available (e.g., the Watershed Ranking Tool) and existing data are being updated (e.g., TRIM II). It is generally quite straightforward to update indicator data as the knowledge base improves. In addition, indicators are frequently consistent with related planning and monitoring approaches, and hence can be easily integrated into other assessment frameworks.

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[1] D.A.A. Toews, Research Hydrologist, Nelson Forest Region, B.C. Ministry of Forests, Nelson, B.C., Pers. comm., 2000.

Cost/timing Due to their relative availability, indicators can provide an efficient means of initial assessment. They can be tailored to available budget and timelines, and can often be applied with available information. Where they are unavailable, this fact can be useful in identifying research needs.

Simplicity Indicators offer objective measures of environmental condition. They are accessible and understandable by both decision-makers and the public—positive characteristics given the complex and controversial nature of watershed hydrology.

2.3.2 Challenges Challenges associated with the use of environmental indicators include the lack of a complete knowledge base, variability in watershed characteristics and management regimes, availability and quality of data, and the development and calibration of adequate assessment techniques.

Knowledge Watershed hydrology is a relatively new science and a work in progress. Knowledge is incomplete and will likely remain so for some time to come. Generalizations can remain difficult, challenging the applied scientist's ability to establish reliable cause-and-effect linkages between management and hydrologic outcomes (Figure 2).

Variability The site factors listed in Table 1 suggest a considerable degree of natural variability—potentially obscuring effects due to management. In addition, management is highly variable in British Columbia's forest industry, both in terms of the "standards of the day," and the quality and extent of implementation.

Data Data availability and quality are concerns that all models must consider. Depending on the scale of the assessment, a variety of data sources are available (provincial, regional, district). Data quality is highly variable.

Calibration Consistent measures of impact are necessary to calibrate the indicators to hydrologic risk. Given the absence of standardized hydrologic impact data, it is necessary to develop strategies for their systematic collection. Possible sources include research, channel assessments, hydrometric records, flooding information, and anecdotal information. Where impact data cannot be interpreted from existing sources, a program of targeted field work can be pursued.

Evaluation The objective measures of impact also support a program of model evaluation. An adaptive-management framework with a constructive feedback loop provides a system of progressive evaluation and opportunity for model improvement. A risk-assessment framework can provide a clear separation of science and values, and can greatly benefit evaluation.

3.1 Summary of Existing Approaches

Cumulative effects are defined in various ways in the literature. According to Sidle and Hornbeck (1991), "…the concept of cumulative effects encompasses those environmental changes caused by the interaction of natural ecosystem processes with the effects of land use activities distributed through time or space, or both." Summed effects differ from cumulative ones in that interactions are involved.

Modelling approaches found in the literature can be summarized as being of three types:

- process models,
- indicator models, and
- checklists/surveys.

Process-based models begin from a theoretical understanding of system behaviour. Given the diversity of natural systems and the complex interactions that are being modelled, process-based models are generally complex, have high data requirements, and typically emerge from a research environment. However, they often provide greater accuracy and broader application across different landscapes and management regimes. Other models use indicators that correlate—at times crudely—to resource degradation. These approaches seek to select indicators that link environmental pressures to changes in environmental values. They tend to be simple to use but narrow in scope, and require recalibration if applied to a different landscape and/or management regime. Checklist/survey approaches are considered too subjective to be of use in the current situation.

3.2 Existing Approaches in British Columbia

Between the mid-1980s and the present, approaches have been developed to address the cumulative hydrologic effects of forest development in British Columbia's Crown forests:

- Watershed Workbook (Wilford 1987)
- Initial IWAP Level 1 (B.C. Ministry of Forests and B.C. Ministry of Environment 1995)
- Interim IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1998)
- Domestic Watershed Guidelines (Kootenay Boundary Land Use Plan)
- Revised IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999)

These approaches use different suites of indicators, as shown in Table 2. The approaches use forest-development indicators in different ways to yield interpretations of hydrologic hazards (e.g., Chatwin 2001).

3.3 Need for a New Approach for Broad-scale Strategic Planning

Ideally, an assessment approach will have a strong theoretical basis that is focused on the landscape and management regime under consideration. The approach should be grounded in the understanding that current research and detailed modelling can provide and should include consideration of spatial attributes. It must be simple in application, and capable of exploiting geographic information system capabilities and available data. It is likely that an indicator approach will be most feasible; however, those indicators selected

TABLE 2 *Indicators used to assess cumulative hydrologic effects: existing approaches in British Columbia*

Indicator	Units	Initial IWAP Level 1	Interim IWAP	Revised IWAP (May/99)	Kootenay-Boundary Land Use Plan
Extent of logging					
% of watershed	% (ha/ha)		✓	✓	
ECA (H60 weighted)	none	✓	✓	✓	✓
Road density					
In entire basin	km/km^2	✓	✓	✓	✓
Above the H60 line	km/km^2	✓			
On erodible soils	km/km^2	✓			
Within 100 m of a stream	km/km^2	✓			
On erodible soils and within 100 m of stream	km/km^2	✓			
On unstable slopes	km/km^2	✓	✓	✓	✓
As high sediment source	km/km^2		✓	✓	
Density of stream crossings	no./km^2	✓	✓		✓
Channel / riparian					
Stream logged	% (km/km)	✓	✓		
Fish stream logged	% (km/km)	✓			
S1/S2/S3/S4 streams logged	% (km/km)			✓	
Stream logged on slopes >60%	% (km/km)	✓			
Streams with unstable channel	% (km/km)		✓	✓	
Other					
Density of landslides	no./km^2	✓	✓	✓	✓

should be tied to relevant physical processes that correlate with impact (Figure 2). It would be best implemented in terms of an adaptive-management framework. Ongoing evaluation, as knowledge and data improve, would give the rating system the capacity to evolve, thereby improving the precision and accuracy of its indications.

The structure should be established so that the results are amenable to interpretation in a risk-assessment context so that "science" and "policy" can be separated clearly. The model would bring to the forefront the consequences of decisions, and illuminate likely outcomes and their desirability. The model would encourage the distribution, and a collective sharing, of responsibility for managing identified risk by making explicit the factors that pose risk to environmental values/resources.

In developing management indices, one index cannot adequately represent the hydrologic complexity. However, if the indices are poorly formulated or lack data or a physical basis, it may be more appropriate to acknowledge the lack of understanding and simply use crude "back of the envelope" calculations based on general indicators such as basin ECA and road density.

4.1 Framework

A framework is proposed for a risk-assessment model consistent with the direction provided in Section 3.3. Physically based, transparent, and easy to modify, the rating system illuminates the risks inherent in policies and management practices. It employs both site and management factors, and is employed in an adaptive-management framework.

4.2 Data Considerations

Table 3 suggests data that may be appropriate for addressing the many factors included in the risk rating scheme.

A variety of data sources is available, depending on scale and forest region (full, partial, potential coverage):

- Watershed Atlas
- Watershed Ranking Tool
- TRIM II, TRIM
- Bedrock/soil/terrain mapping
- Region-specific studies (e.g., terrain attribute study)
- Terrain stability mapping
- Biogeoclimatic Ecosystem Classification mapping
- Satellite imagery
- Forest cover mapping
- Natural disturbance types
- Water quality/quantity data
- Forest Development Plans
- Silvicultural data (MLSIS/ISIS)
- Climate data

TABLE 3 *Factors to be rated and their associated potential data sources*

Regime			Factor of interest	Surrogate for modelling purposes
Site factors	Flow		Climatic regime (precipitation, ET, storm frequency, etc.)	Biogeoclimatic subzones Index of aspect/elevation complexity[a]
			Snowmelt patterns	Glaciers and snowfields
			Low-flow generators	Wetlands, high-elevation lakes
			Vulnerability to ECA	% naturally forested
		Sediment	Susceptibility to disturbance	Basin morphology[a]
			Soil moisture storage	Soil depth/texture
			Flow/sediment buffering	Wetlands & lakes
			Channel vulnerability	Channel index[a]
			Vulnerability due to fire	Recent fire history; NDT patterns
			Sediment yield due to mass wasting	Class III, IV, and V terrain stability and LISS
			Sediment yield due to surface erosion	Waterborne-erosion potential: M, H, VH (includes delivery)
			Flood disturbance	Flood history Debris-flood potential
			Sediment input	Glaciers
Development factors	Road-building		Peak flows	Total road density
			Channel stability	Roads on erodible soils
			Suspended sediment	Roads on unstable soils
			Low flows	Roads near streams
				Quality of road construction[a]
	Forest removal		Peak flows, low flows	Weighted ECA
			Channel stability, suspended sediment	Riparian logging

[a] These items represent data interpretations that require some analysis and development.

ET = evapotranspiration. NDT = Natural Disturbances Types. LISS = Landslide-Induced Stream Sedimentation.

4.3 Rating Keys

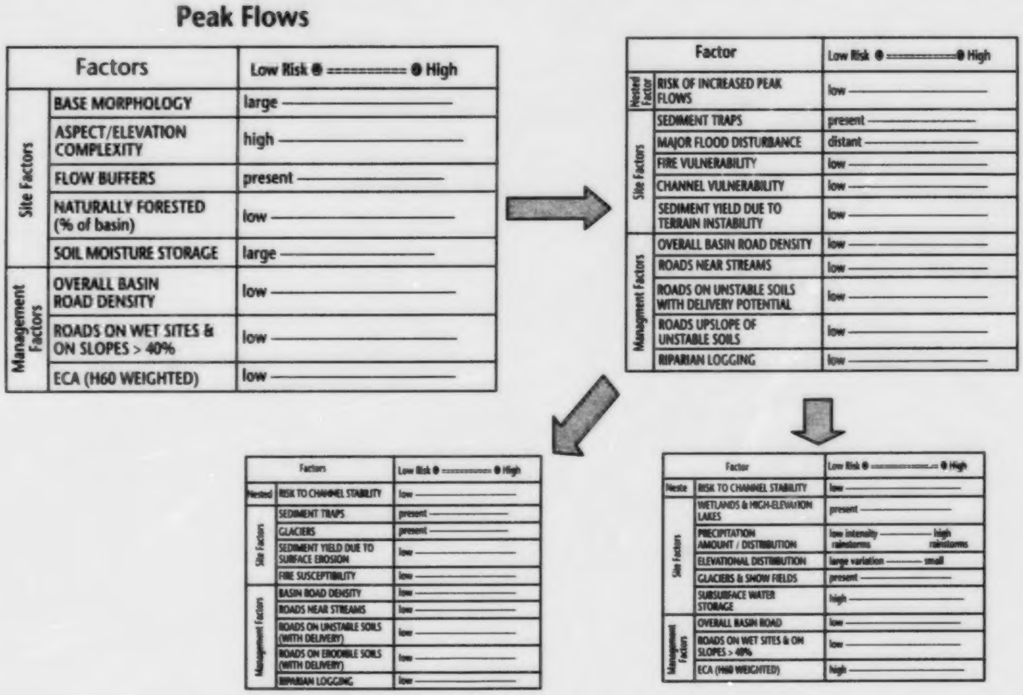
Nested, hierarchical keys are proposed as the basis for a rating system of hydrologic risk (see Figure 3. This format is amenable to easy modification as knowledge increases, and hence is appropriate in an adaptive-management context. It is also highly transparent in regard to the weighting of hydrologically important factors. Where interactions are important, separate combined factors can be included.

The four keys are provided in Tables 4a through 4d. The keys for peak flow and low flow can be completed independently of other keys to yield risks that higher peak flows and lower low flows could occur due to a specific level of forest development in a specific watershed. The risk of peak-flow changes can be used in the channel stability key to yield a rating of the risk that the channel will be destabilized. Lastly, the risk to channel stability can be put into the suspended sediment key to yield a rating of the risk of increased suspended sediment.

4.4 Calibration

With the risk-rating keys developed conceptually and the input data in place, calibration follows. Calibration is best done in an iterative way with both input and impact data. An adaptive-management framework facilitates the effective integration of impact data during model development and calibration.

The rating system assumes a base case defined by the historic range of natural variability. This may be difficult due to a lack of data and may rely on professional judgement. To strengthen the rationale used to establish the ratings, consistent measures of watershed impact are needed, preferably in each of the four categories. A measure of peak-flow change is extremely difficult to gather because data are sparse, and where data are available, analysis for changes in peak flows due to forest development is difficult. Hence for the peak-flow key, it is suggested that reliance be made on the research literature



Peak Flows

Factors		Low Risk ● ========= ● High
Site Factors	BASE MORPHOLOGY	large ———
	ASPECT/ELEVATION COMPLEXITY	high ———
	FLOW BUFFERS	present ———
	NATURALLY FORESTED (% of basin)	low ———
	SOIL MOISTURE STORAGE	large ———
Management Factors	OVERALL BASIN ROAD DENSITY	low ———
	ROADS ON WET SITES & ON SLOPES > 40%	low ———
	ECA (H60 WEIGHTED)	low ———

Factor		Low Risk ● ========= ● High
Nested Factor	RISK OF INCREASED PEAK FLOWS	low ———
Site Factors	SEDIMENT TRAPS	present ———
	MAJOR FLOOD DISTURBANCE	distant ———
	FIRE VULNERABILITY	low ———
	CHANNEL VULNERABILITY	low ———
	SEDIMENT YIELD DUE TO TERRAIN INSTABILITY	low ———
Managment Factors	OVERALL BASIN ROAD DENSITY	low ———
	ROADS NEAR STREAMS	low ———
	ROADS ON UNSTABLE SOILS WITH DELIVERY POTENTIAL	low ———
	ROADS UPSLOPE OF UNSTABLE SOILS	low ———
	RIPARIAN LOGGING	low ———

Factors		Low Risk ● ========= ● High
Nested	RISK TO CHANNEL STABILITY	low ———
Site Factors	SEDIMENT TRAPS	present ———
	GLACIERS	present ———
	SEDIMENT YIELD DUE TO SURFACE EROSION	low ———
	FIRE SUSCEPTIBILITY	low ———
Management Factors	BASIN ROAD DENSITY	low ———
	ROADS NEAR STREAMS	low ———
	ROADS ON UNSTABLE SOILS (WITH DELIVERY)	low ———
	ROADS ON ERODIBLE SOILS (WITH DELIVERY)	low ———
	RIPARIAN LOGGING	low ———

Factor		Low Risk ● ========= ● High
Neste	RISK TO CHANNEL STABILITY	low ———
Site Factors	WETLANDS & HIGH-ELEVATION LAKES	present ———
	PRECIPITATION AMOUNT / DISTRIBUTION	low intensity rainstorms ——— high rainstorms
	ELEVATIONAL DISTRIBUTION	large variation ——— small
	GLACIERS & SNOW FIELDS	present ———
	SUBSURFACE WATER STORAGE	high ———
Management Factors	OVERALL BASIN ROAD	low ———
	ROADS ON WET SITES & ON SLOPES > 40%	low ———
	ECA (H60 WEIGHTED)	high ———

FIGURE 3 *Illustration of relationships between nested rating keys.*

TABLE 4 *Rating keys for determination of risk due to peak flow, channel stability, low flow, and suspended sediment*

A)	Peak flow factors	Low risk	← = →	High risk
site factors	Basin size	large		small
	Aspect/elevation complexity	high		low
	Flow buffers	present		absent
	Naturally forested (% basin)	low		high
	Soil moisture storage	large		minimal
management factors	Overall basin road density	low		high
	Roads on wet sites & on slopes >40%	low		high
	ECA (H60 weighted)	low		high

B)	Channel stability factors	Low risk	← = →	High risk
nested factor	Risk of increased peak flows	low		high
site factors	Sediment traps	present		absent
	Major flood disturbance	distant		recent
	Fire vulnerability	low		high
	Channel vulnerability	low		high
	Sediment yield due to terrain instability	low		high
management factors	Overall basin road density	low		high
	Roads near streams	low		high
	Roads on unstable soils with delivery potential	low		high
	Roads upslope of unstable soils	low		high
	Riparian logging	low		high

C)	Low flow factors	Low risk	← = →	High risk
nested factor	Risk to channel stability	low		high
site factors	Wetlands & high-elevation lakes	present		absent
	Precipitation amount/distribution	low-intensity rainstorms		high-intensity rainstorms
	Elevational distribution	large variation		small variation
	Glaciers & snow fields	present		absent
	Subsurface water storage	high		low
management factors	Overall basin road density	low		high
	Roads on wet sites & on slopes >40%	low		high
	ECA (H60 weighted)	high		low

TABLE 4 *Continued*

D)	Suspended sediment factors	Low risk	← = →	High risk
nested factor	Risk to channel stability	low		high
site factors	Sediment traps	present		absent
	Glaciers	present		absent
	Sediment yield due to surface erosion	low		high
	Fire susceptibility	low		high
management factors	Basin road density	low		high
	Roads near streams	low		high
	Roads on unstable soils (with delivery)	low		high
	Roads on erodible soils (with delivery)	low		high
	Riparian logging	low		high

(see Section 4.2.2). Assessment of channel-stability ratings can be developed and applied particularly to watersheds for which there is already significant forest development. Available channel assessments, flooding records, anecdotal information, and field work (if necessary) can be used in the assessments. The suspended-sediment key can benefit from an impact assessment based on water-quality data, water-user interviews, and professional opinions provided in IWAP reports. Water-user interviews, in addition to the research literature, can be used for the low-flow key. Where the appropriate impact index is weak, a limitation of the rating system is suggested.

Several examples of research in the Nelson Forest Region supporting such calibrations are provided in these proceedings. Gluns (2001) describes his observations of snowline retreat during freshet and its timing in relation to occurrence of peak flow. Jordan (2001a) provides preliminary observations from a regional study attempting to calibrate landslide frequency to terrain attributes. Jordan (2001b) describes water-quality measurements that, combined with data from other regional monitoring, may be useful in developing expectations of sedimentation rates in relation to watershed and development factors. Henderson and Toews (2001) and Bird (2001) have looked in detail at specific sites at the sediment-source and riparian components of a watershed assessment. Their work may be useful in developing generalized patterns of potential watershed impact. These types of research projects should help provide practical interpretations on which to base scoring in the risk-assessment keys at a scale at which decision-making is taking place.

4.5 Interpretation

In the proposed approach, calibration of the risk ratings is carried out to yield interpretations, as per Table 5. In this table, "significant changes to the hydrologic regime" is interpreted to mean the occurrence of one or more of the following as a result of forest development:

- increased peak flows (greater than 10%),
- significant changes in channel stability,
- significant changes in water quality, and/or
- significant changes in aquatic habitat,

where "significant" refers to being outside the natural range of variability or beyond a defined threshold.

TABLE 5 *Definitions of risk ratings*

Risk rating	Definition			Probability of significant hydrologic impact (%)
Very low	The assessed level of forest development	is highly unlikely to	have caused, or cause in the future, changes to the hydrologic regime.	<5
Low		is unlikely to		5–25
Moderate		may		25–50
High		is likely to		50–75
Very high		is highly likely to		>75

TABLE 6 *Potential responses in relation to risk outcome*

Risk rating	Possible response
VL	Few or no constraints
L	Minor constraints
M	Modify development; consider field work[a]
H	Modify and/or defer development; consider field work[a]
VH	Defer development and rehabilitate; consider field work[a]

[a] Where a rating is designed to suggest caution in pursuing further development, it may be appropriate to pursue field work to investigate the watershed-specific need to modify and/or defer development.

Table 6 provides suggested general responses in relation to risk level. This table can be used as a guide. After risk ratings have been determined, the implications for forest management may justify follow-up field work to investigate rating accuracy and better select the management response.

In the absence of field information, and as a planning tool, these risk interpretations can enable better resource use and allocation. They should not, however, be interpreted as a replacement for site-specific watershed studies. No matter how well calibrated the risk-assessment tool becomes, knowledge gaps will likely persist and can continue to result in misdiagnoses at certain sites.

5 CONCLUSIONS

This paper has reviewed the use of hydrologic indicators in British Columbia within the general context of approaches available for assessing hydrologic risk. The benefits and challenges associated with using indicators in hydrologic risk assessment were presented, specifically in regard to the application of broad-scale strategic planning such as the Timber Supply Review. A practical option for improving the quality of hydrologic information provided to decision-makers has been presented.

Four conclusions can be reached from this paper:

1. There is a need for improved consideration of hydrologic risk in development planning over various scales.

2. Indicators offer the potential to better utilize existing hydrologic information to support improved decisions and, in the short term, provide a recognition of risks inherent in those decisions.
3. Challenges exist to using indicators, notably the lack of systematic measures of impact.
4. A framework is available to initiate the development of a provincial approach.

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Effects of Changes in Forest Cover on Streamflow: A Literature Review

ROB SCHERER

ABSTRACT

The Interior Watershed Assessment Procedure that is used in British Columbia relies heavily on the use of Equivalent Clearcut Area as a tool to estimate potential hydrologic impacts of forest development on peak flows. The purpose of this literature review was to summarize the results of numerous watershed experiments that have explored the relationship of changes in forest cover to changes in spring freshet peak flows, the timing of peak flows, water yield, and low flows. This review included only snowmelt-dominated watersheds that are situated within western Canada and the United States and that could be related to watersheds located within the central and southern interior of British Columbia. The review indicated highly variable changes in: peak flow (ranging from no change to 66% increase), peak-flow timing (ranging from no change to 18 days advancement), water yield (ranging from no change to 111% increase), and low flow (ranging from no change to 37% increase). Also, there was no consistent relationship between forest-cover removal and the above hydrologic variables.

1 INTRODUCTION

The Interior Watershed Assessment Procedure (IWAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) that is used in British Columbia relies heavily on the use of Equivalent Clearcut Area (ECA) as a tool to estimate potential hydrologic impacts of forest development on peak flows. The purpose of this literature review was to compile the results of numerous watershed experiments that have explored the relationship of changes in forest cover to changes in spring freshet peak flows that are related to the effects of managed disturbances (e.g., logging and road-building) as well as natural disturbances (e.g., wildfire and defoliation by insects). Streamflow data that related to forest-cover changes and the timing of peak flows, annual water yields, and low flows were also included in this literature review. The intent in compiling this information was to improve the general understanding of the use of ECA as a tool in the determination of potential changes to streamflows and to improve management guidelines for interior British Columbia watersheds.

This review included only snowmelt-dominated watersheds that are situated within western Canada and the United States and that could be related to watersheds located within the central and southern interior of British Columbia. More than 40 papers were reviewed for this project; 17 papers met the local criteria for this report.

2 METHODS

Watershed catchment studies were summarized by location, forest type, elevation range, general watershed aspect, average annual streamflow, drainage area, percent forest removed, average percent change in annual water yield, average percent change in maximum peak flow generated during the spring freshet period, average annual peak-flow advancement (days), average percent change in low flows, and forest-cover removal method (e.g., silviculture system or natural disturbance type).

Data were compiled as recorded in the literature for average changes in annual maximum peak flow, timing of peak flow, annual water yield, and low flows. Graphing and simple linear regression were used to determine if there was a direct relationship between streamflows and forest-cover removal. All of the regressions were forced through the origin since no removal of forest cover was assumed to have no effect on streamflows.

Multiple linear regression using backward variable elimination was used to explore if there was a relationship between streamflow changes with the amount of forest cover removed and drainage area. This relationship was explored since the common belief is that detectable increases in streamflows (i.e., peak flows and water yields) are inversely related to the drainage area of a watershed. That is, the smaller the watershed area, the larger the increase detected in streamflow at a certain level of forest cover removed. Relationships using other variables were not recorded in this assessment since the data set was relatively small due to gaps in the data.

Rain-dominated peak flows during summer months were not included in this analysis. No attempt was made to separate the impacts of roads on streamflows from the impacts of forest removal since there was limited research that addressed only the impacts of roads.

It should be noted that the amount of forest cover removed was assumed to be directly related to ECA. No attempt was made to account for hydrologic recovery in the various studies reviewed since information relating to the tree regeneration on individual treatment units within a study watershed was not documented in the literature. The above assumption should be valid since most of the post-treatment streamflow data were collected over a 2- to 20-year period, making the amount of hydrologic recovery over the study period small.

For research studies that identified the amount of basal area removed (e.g., partial harvest cutblocks), the amount of forest cover removed was based on the following criteria for calculation of ECA: 0–30% basal area removal was considered as 0% forest cover removed; 30–60% basal area removal was considered as 50% forest cover removed; and greater than 60% basal area removal was considered as 100% forest cover removed. These criteria were based upon the original *Interior Watershed Assessment Procedure Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1995) for calculation of ECA.

For the purposes of this project, relevant articles included statistical analysis of streamflow changes that could be related to snowmelt-dominated watersheds within the central and southern interior of British Columbia. Therefore, the literature review was confined to watersheds that met the following criteria:

- predominantly covered with coniferous forest types such as lodgepole pine, Engelmann spruce, Douglas-fir, white fir, subalpine fir, ponderosa pine, and grand fir,
- utilized controlled experiment techniques (e.g., paired watershed studies with post- and pre-treatment comparisons, double mass curves, or time series analysis), and
- located within Utah, Idaho, Colorado, eastern Oregon, eastern Washington, east side of Rocky Mountains in Alberta, central British Columbia, and Arizona.

3 MAJOR FINDINGS

The review findings are summarized in tabular format in Appendix 1. It should be noted that the studies were compiled and summarized as published. No judgement was made on the quality of the research and no attempt was made to add further data that were not already published.

3.1 Peak Flow

In climates where snow melt is a major factor in generating peak flows, forest-cover removal has been shown to have a significant effect on snow accumulation, and the timing and rate of snow melt (Golding and Swanson 1986; Troendle et al. 1988; Hardy and Hansen-Bristow 1990). One of the typical assumptions that has been used in the IWAP is that there is a direct relationship in an increase in peak flow with the amount of forest cover removed. However, based upon this literature review, the relationship between the amount of forest cover removed to the increased peak flows is highly variable, as shown in Figure 1. In non-statistical terms, the average percent

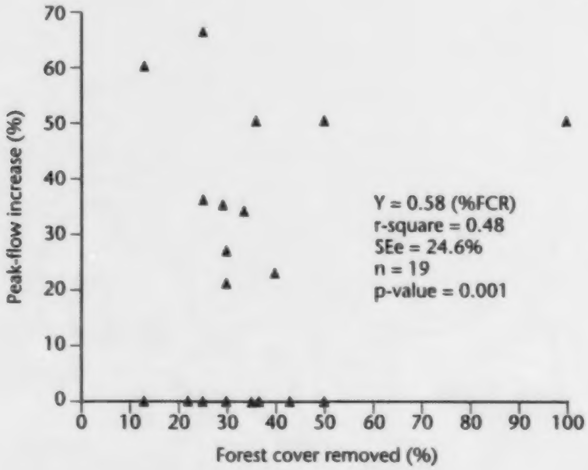

FIGURE 1 *Percent increase in peak flow associated with the percent of forest cover removed.*

increase in peak flow ranged from no increase to a maximum increase of 66%, and correlated poorly with the amount of forest removed. This poor correlation is highlighted in the relatively large standard error of the estimate (i.e., SE = 24.6%). The standard error of the estimate gives an indication of how far the observations are spread around the regression line. The scatter in the plot is not unexpected, however, given the wide range in watershed size and watershed characteristics.

This wide variation in response is also consistent with a literature review completed by MacDonald et al. (1997).[1] MacDonald et al. compiled more than 120 publications that represented more than 60 research sites and 120 treated catchments. This literature review included data from coastal and interior watersheds as well as data for changes in peak flows that were generated throughout the entire year. As shown in Figure 2, there is not a consistent relationship between the percent of a basin that had been harvested with the percent change in peak flows. The peak-flow increases greater than 150% occurred generally in the growing season when wetter antecedent soil-moisture conditions can occur after forest harvesting. MacDonald et al. also stated "… that peak flows are generally much smaller during the growing season and this means that a small increase in absolute discharge can yield very large increases in percentage terms."

Our data were further analyzed by using multiple linear regression to determine if there was a relationship between changes in peak flow to the amount of forest cover removed and the drainage area of the studied watersheds. At a 95% significance level, drainage area was not significant in explaining the percent change in peak flows. Therefore, based on this information, drainage basin area does not appear to be a factor in explaining the relationship between changes in peak flow and the amount of forest cover removed.

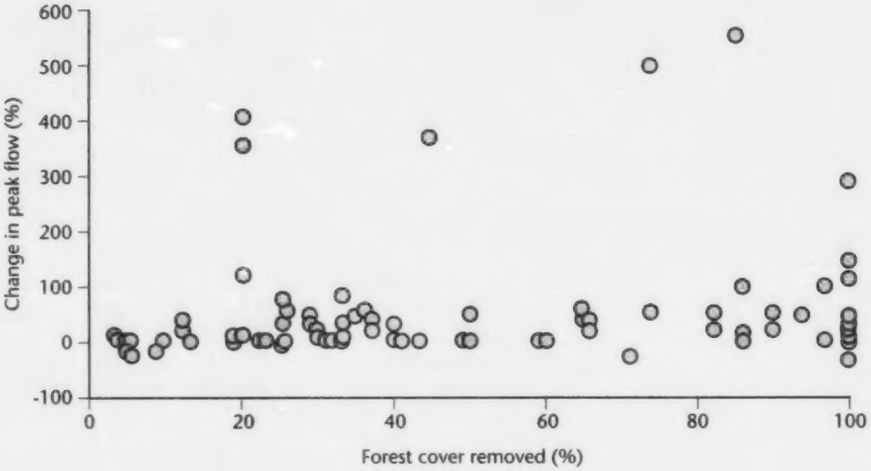

FIGURE 2 *Percent change in the size of peak flows as a function of the percent forest cover removed (adapted from Macdonald et al. 1997).*

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[1] MacDonald, L.H., E.E. Wohl, and S.W. Madsen. 1997. Validation of water yield thresholds on the Kootenai National Forest, final report. Colorado State University, Fort Collins, Colorado. Unpublished Report.

3.2 Timing of Peak Flows

Forest-cover removal has been shown to have a significant effect on snow accumulation and on the timing and rate of snow melt. It has been shown that the ratio of snow melt rates in the forest to those in the openings ranges between 0.4 and 1 with 0.7 being the most frequent value (Winkler 1999). Given this faster rate of snow melt in forest openings one might expect to see an advancement in the timing of peak flows. However, based on this compilation of research literature, the average date at which peak flows occurred in the post-treatment periods ranged from an advancement of 18 days to no change in the date of peak compared to the control watersheds (Figure 3). Once again the response to changes in forest cover was found to be highly variable.

3.3 Annual Water Yield

It is generally understood that manipulation of vegetation cover has a direct impact on the interception and evapotranspiration components of the hydrologic cycle. Annual water yield increases with a reduction in forest cover related to natural or managed disturbances. Several research papers have shown the general relationship of increased annual water yield associated with forest removal (Hibbert 1967; Bosch and Hewlett 1982; Stednick 1996).

In this report, a graphical relationship of increased water yield with the percent forest cover removed for snow-dominated watersheds is shown in Figure 4. Similar to the data shown for percent changes in peak flow, the percent increase in water yield related to the amount of forest cover removed is also highly variable. The average percent increase in annual water yield ranged from no increase to a maximum increase of 111%, and correlated poorly with the amount of forest removed. This poor correlation can be seen in the large standard error of the estimate (i.e., SE = 30%) that was calculated for the simple linear relationship.

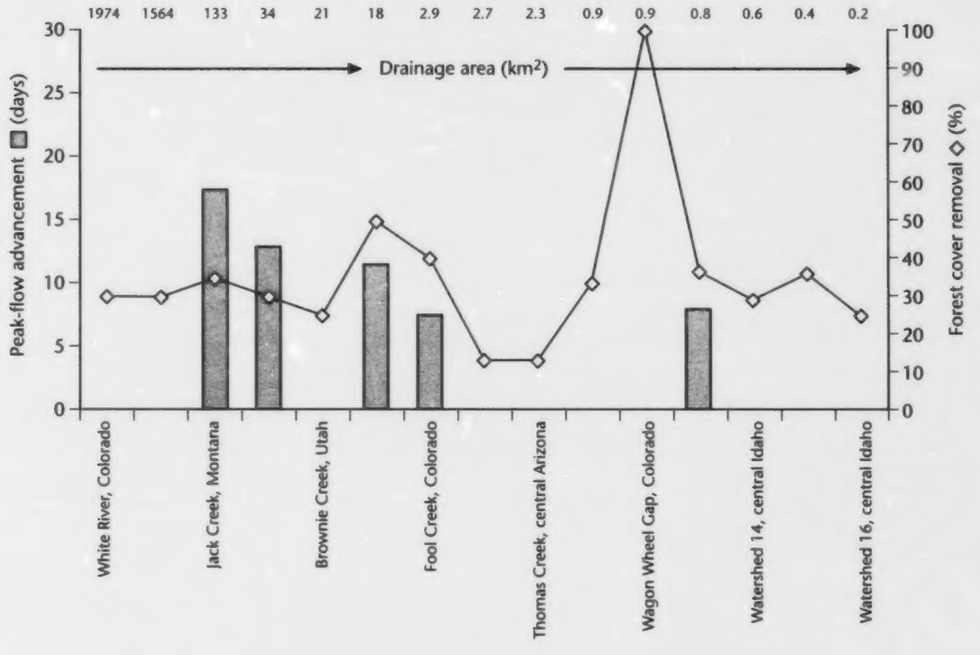

FIGURE 3 *Average number of days that peak flow advanced in the post-treatment period as compared to the control watersheds. Percent of forest cover removed is shown as a line with watershed drainage area decreasing from left to right.*

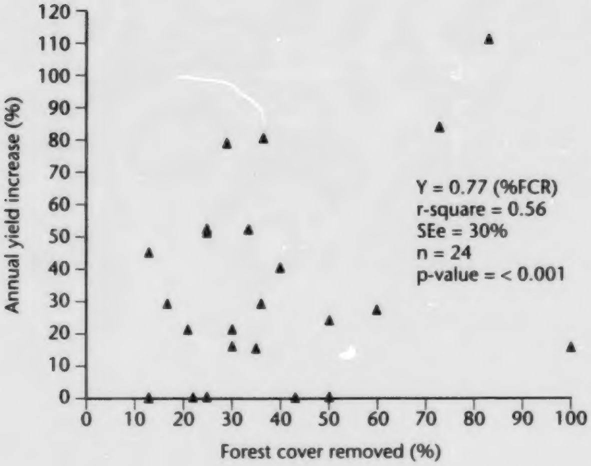

FIGURE 4 *Percent increase in annual yield as compared to the percent of forest cover removed.*

The simple linear relationships found in our data are similar to Stednick's (1996) compilation of literature. Stednick found a significant relationship (r-square = 0.01, SE = 66 mm, p-value = 0.0001) between the amount of forest cover removed and the unit increase in annual water yield. Stednick's study was based upon 35 watersheds within the Rocky Mountain/Inland Intermountain region of the United States, and yielded the following stated relationship:

> *The Rocky Mountain/Inland Intermountain region data suggest that a 15% harvest area results in a measurable annual water yield increase. When 50% of the catchment was harvested, annual water yield increase ranged from 25 to 250 mm and complete harvesting (100%) increased annual water yields from zero to over 350 mm. The results are variable, especially above 30% harvested.*

Similar to the peak-flow data, multiple linear regression was used to determine the relationship between the increased water yield with percent forest cover removed and the drainage area. Once again, drainage area was not significant in explaining the variation in the percent increase in annual yield.

3.4 Low Flows

Increases in low-flow amounts are cited as being related to the reduction in evapotranspiration as result of the removal of forest cover. The loss in evapotranspiration subsequently increases the available volume of water that can generate low flows. In this review of literature there was limited research that explored the effects of forest-cover removal on low streamflow periods (summer and fall). Six of the articles reviewed included an analysis of low-flow data. These studies showed that the average low-flow increase ranged between 37% and zero (Figure 5). None of the studies showed a decrease in low flows.

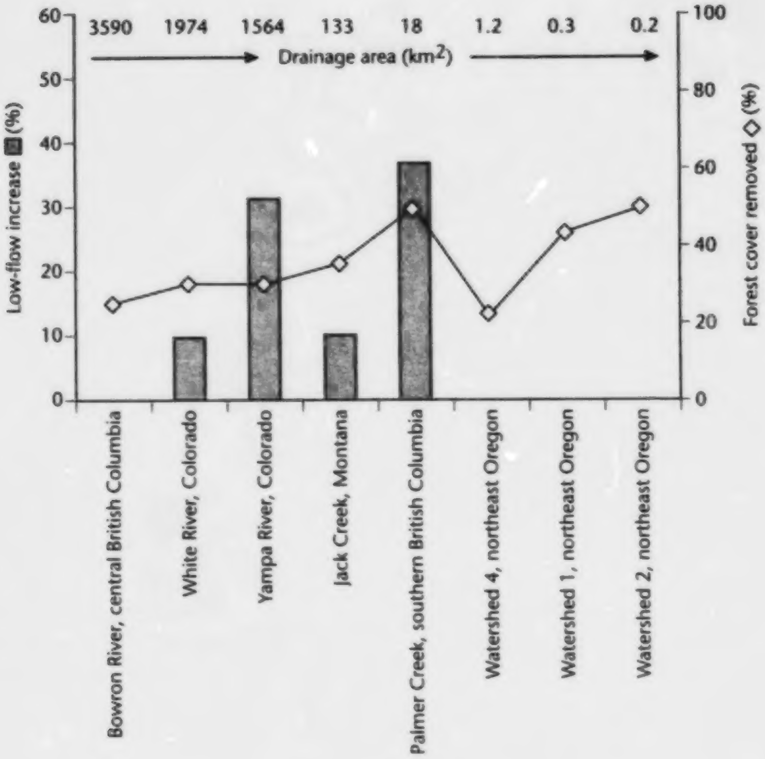

FIGURE 5 *Average percent increase in low flow from six study watersheds. Percent of forest cover removed is shown as a line, with watershed drainage area decreasing from left to right.*

4 CONCLUSION

Based upon research conducted east of the Cascade and Coast Range mountains within western Canada and the United States, it is clear that the removal of forest cover as a result of either natural or managed disturbances can have an impact on streamflows. However, the research has shown that the response of peak flows, annual water yields, and low flows to changes in forest cover are highly variable. Streamflow changes range from being insignificant to large, with no apparent direct correlation with the amount of forest removed as the sole variable.

It is unlikely that further statistical review will determine what the differences are between the group of studies. In the interim, until our understanding of the mechanisms that generate streamflows improves, it is important that ECA as a predictor of streamflow change be used with caution. Until the interrelationship of the mechanisms that generate or change streamflows is clearly understood for a specific watershed, ECA should not be used in isolation of a direct understanding of the physical conditions of the watershed.

5 ACKNOWLEDGEMENTS

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APPENDIX 1 Summary table

Watershed	Author (Year)	Forest type	Elevation range (m)	Annual streamflow (mm)	Drainage area (km^2)	Forest removal (assumed) (%)	Average annual water (mm)	Average annual water (%)	Average annual peak flow (m^3/s)	Average annual peak flow (%)	Average annual peak flow (days)	Average low-flow increase (mm)	Average low-flow increase (%)	Forest removal method	Aspect	Average annual precip. (mm)
Ochoco Creek, Central Oregon	Berndt et al. (1970)	Ponderosa pine	945–2133	N.A.	765	Not determined	56	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	CC, SW	W	635
White River, Colorado	Bethlahmy (1975)	Engelmann spruce and subalpine fir	N.A.	N.A.	1974	30	37.9	15.7	20.2	27	0	1.25	9.6	Beetle epidemic (no harvesting)	W	N.A
Yampa River, Colorado	Bethlahmy (1975)	Lodgepole pine	N.A.	N.A.	1564	30	35.2	15.8	0	0	0	1.6	31.5	Beetle epidemic (no harvesting)	N	N.A.
Brownie Creek, Utah	Burton (1997)	Lodgepole pine	Average 3082	N.A.	21.3	25	147	52	1.6	66	0	N.A.	N.A.	CC	SE	787
Palmer Creek, southern British Columbia	Cheng and Bondar (1984)	Douglas-fir, lodgepole pine, Engelmann spruce, and subalpine fir	1400–1750	71	18	50	83.5 (April–August)	24	N.A.	50	5–18	N.A.	37	Severe forest fire	E	1000
Camp Creek, southern British Columbia	Cheng (1989)	Lodgepole pine	880–1920	140	33.9	30	29	21	0.25	21	13	N.A.	N.A.	CC	S	600
Watershed 1, NE Oregon	Fowler et al. (1987)	Mixture of conifers	1439–1617	N.A.	0.29	43	0	0	0	0	N.A.	0	0	CC	NE	1429
Watershed 2, NE Oregon	Fowler et al. (1987)	Mixture of conifers	1439–1617	N.A.	0.24	50	0	0	0	0	N.A.	0	0	SW	NE	1429
Watershed 4, NE Oregon	Fowler et al. (1987)	Mixture of conifers	1439–1617	N.A.	1.18	22	0	0	0	0	N.A.	0	0	CC, PC	NE	1429
Thomas Creek, central Arizona	Gottfried (1991)	Mixture of conifers	2545–2819	82	2.27	13	44	44.8	0.06	59.8	0	fewer no-flow days	fewer no-flow days	PC, CC	S	768
Watershed 12, central Idaho	King (1989)	Grand fir	1574	440	0.8	36.6	N.A.	80.1	0	0	8	N.A.	N.A.	CC	S	1168
Watershed 14, central Idaho	King (1989)	Grand fir	1596	440	0.6	29.2	N.A.	78.7	0.03	35	0	N.A.	N.A.	CC	S	1168
Watershed 16, central Idaho	King (1989)	Grand fir	1659	440	0.2	25	N.A.	51.2	0.01	36	0	N.A.	N.A.	CC	S	1168

Watershed	Author (Year)	Forest type	Elevation range (m)	Annual streamflow (mm)	Drainage area (km^2)	Forest removal (assumed) (%)	Average annual water (mm)	Average annual water (%)	Average annual peak flow (m^3/s)	Average annual peak flow (%)	Average annual peak flow (days)	Average low-flow increase (mm)	Average low-flow increase (%)	Forest removal method	Aspect	Average annual precip. (mm)
Watershed 18, central Idaho	King (1989)	Grand fir	1664	440	0.9	33.4	N.A.	52	0.04	34	0	N.A.	N.A.	CC	S	1168
Castle Creek, eastern Arizona	Lowell (1972)	Ponderosa pine	2388–2616	N.A.	3.6	17	Range between 36 and 10 mm	29	N.A.	N.A.	N.A.	N.A.	N.A.	CC	SE	639
Jack Creek, Montana	Potts (1984)	Lodgepole pine	1900–3000	305	133	35	N.A.	15	0	0	14–21	N.A.	10	Beetle epidemic (no harvesting)	W	347
North Fork to Workman Creek, central Arizona	Rich and Gottfried (1976)	Ponderosa pine, white fir, Douglas-fir	2010–2356	84	1	73	69	84	N.A.	N.A.	N.A.	N.A.	N.A.	CC	SW	835
South Fork to Workman Creek, central Arizona	Rich and Gottfried (1976)	Ponderosa pine, white fir, Douglas-fir	2010–2356	84	1.3	83	93	111	N.A.	N.A.	N.A.	N.A.	N.A.	PC, wildfire, CC	NW	835
18 watersheds, Rocky Mountains, Alberta	Swanson and Hillman (1977)	Lodgepole pine	1110–1770	167	7–23.9	35–84	39.2	27	N.A.	N.A.	N.A.	N.A.	N.A.	CC	Variable	525
Cabin Creek, Alberta	Swanson et al. (1986)	Spruce, fir, and lodgepole pine	1730–2800	310	2.12	21	17	21	N.A.	N.A.	N.A.	N.A.	N.A.	CC	E	840
Fool Creek, Colorado	Troendle and King (1985)	Spuce, fir, and lodgepole pine	2927–3810	N.A.	2.89	40	82	40	0.055	23	7.5	N.A.	N.A.	CC	N	732
Deadhorse Creek, Colorado	Troendle and King (1987)	Spuce, fir, and lodgepole pine	2880–3536	N.A.	2.7	13	0	0	0	0	0	N.A.	N.A.	CC, PC	E	N.A.
N. Fork to Deadhorse Creek, Colorado	Troendle and King (1987)	Spuce, fir, and lodgepole pine	2880–3536	N.A.	0.41	36	60	29	0.013	50	0	N.A.	N.A.	CC	S	N.A.
Wagon Wheel Gap, Colorado	Van Haveren (1988)	Not given	2818–3461	156	0.9	100	24.6	15.4	N.A.	50	0	N.A.	N.A.	CC	NE	535
Bowron River, central British Columbia	Wei and Davidson (1998)	Lodgepole pine	N.A.	N.A.	3590	25	0	0	0	0	N.A.	0	0	CC	Variable N	N.A.

Forest Influences on Snow: Preliminary Results on Effects of Regrowth

RITA D. WINKLER

ABSTRACT

In British Columbia, snow accumulation and snow melt dominate the hydrology of most interior watersheds. Both the amount of snow accumulation and the rate of melt vary with forest cover, and its removal and regrowth. For regulatory purposes, the complex relationships between forest cover, snowpack processes, and the risk of elevated spring flows are currently approximated by the single forest inventory variable, tree height. Field data from Mayson Lake and Upper Penticton Creek indicate that tree height alone explains little of the variability in snow accumulation or melt measured under various forest cover types relative to the open. Of the inventory variables measured, crown volume, length, and density explained the largest proportion of the variability in snow accumulation in the forest relative to the open, and the square root of basal area was the best predictor of melt. Work to develop a method of evaluating hydrologic recovery over a broader geographic area and range of forest cover types continues.

INTRODUCTION

In the interior of British Columbia, melting snow generates the spring hydrograph peaks characteristic of most streams. Forest cover removal in snow-dominated watersheds, through logging, fire, insects, or disease, has been shown to increase annual water yield and spring peak streamflow (Bosch and Hewlett 1982). Depending on the size and extent of forest cover removal, 10–70% greater accumulations of snow (expressed as snow water equivalent [SWE]) have been reported (Golding and Swanson 1986; Toews and Gluns 1986). Increases in the melt rate vary from none to double (Winkler 1999). With forest regrowth, both snow accumulation and melt decrease relative to the open. Hardy and Hansen-Bristow (1990) found a 34% higher maximum SWE and a 76% higher melt rate in the clearcut than in a mature spruce-fir forest. In a 4-m-tall lodgepole pine stand, SWE and melt rates were reduced from those in the clearcut by 4 and 6%, respectively. In a 14-m-tall lodgepole pine stand, SWE and melt rates were 14 and 36% less than in the clearcut. In coastal Douglas-fir, Hudson (2000) predicted "recovery" in snow accumulation and snow melt combined to be 75% once the stand was 8 m tall with 45% crown closure.

In British Columbia's watershed assessment procedure (B.C. Ministry of Forests and B.C. Ministry of Environment 1999), spring peak streamflows and forest cover are linked using the concept of "hydrological recovery." Hydrological recovery is defined as "the process by which regeneration restores the hydrology of an area to pre-logging conditions" (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). It further explains that complete recovery involves all components of the hydrologic cycle but "because peak flows in... interior... areas tend to be generated by conditions of radiation snowmelt... snowpack recovery is used as an index of true hydrological recovery." Snowpack recovery is evaluated by the average tree height of the main canopy, a variable that is readily obtainable through the forest inventory system. Though average tree height provides some indication of snow interception and shade, it does not necessarily reflect crown surface area, canopy density, or stem distribution, which are stand characteristics known to influence snowpack processes. In local examples, tree height accounted for only 9–13% of the variability in the ratio of forest to open snow accumulation and 19–44% of the variability in average melt rates between the study stands, depending on year. These values indicate that forest characteristics, or environmental variables, not reflected by tree height have a larger influence on snowpack processes.

Quantifying the relationships between forest structure and snowpack processes for forest-planning purposes is the focus of ongoing research throughout the province. From 1995 through 1997, intensive snow and forest inventory surveys were undertaken at Mayson Lake and at Upper Penticton Creek. This paper provides a preliminary summary of the data from both locations in mature and juvenile lodgepole pine and Engelmann spruce–subalpine fir stands, as well as in adjacent clearcuts.

BACKGROUND

Snow accumulation and melt vary from year to year and from location to location, and with the weather, geographic position, elevation, aspect, topography, and forest cover. Over large distances, elevation is the variable that has the greatest effect on snow accumulation. However, over small distances, the influence of forest cover becomes significant (Meiman et al. 1968).

Forest vegetation affects snow deposition, snow redistribution, and the exchange of energy to the snow surface. Compared to open ground or low-growing forms of vegetation, forests have large intercepting and radiating surface areas. For example, the surface area of a boreal spruce-fir canopy has been approximated as 1800 times larger than that of snow on the ground (Pomeroy and Schmidt 1993). Consequently, conversion from one cover type to another could have a large influence on both snow accumulation and melt (McKay and Gray 1981).

The structure or physical characteristics of a forest vary with species composition, site, age, stand health, and silvicultural treatments. Stands are commonly described by variables such as tree height, stem density, crown volume, and canopy closure. Since snow accumulation and melt rates under different forest types have been shown to differ by up to 50% of that in the open (Bunnell et al. 1985; Toews and Gluns 1986; Winkler 1999) (Table 1), it is generally assumed that structural differences among forest types contribute either directly or indirectly to the differences in the snowpack beneath them.

TABLE 1 *April 1 snow water equivalent (SWE) and average melt rates, summarized as the ratio of measurements under forest cover to those in the open, for snow research in forests similar to those in southern British Columbia*

	April 1 SWE		Average melt rate	
	Pine[1]	**Spruce-Fir**	**Pine**	**Spruce-Fir**
Number of papers reviewed	18	11	4	6
Mature forest cover				
Average forest to open ratio	0.8	0.7	0.6	0.6
Range of forest to open ratios	0.6–1	0.5–0.9	0.4–0.8	0.5–0.8
Juvenile forest cover				
Average forest to open ratio (less than 8-m-tall ponderosa pine)	1		0.7	
Average forest to open ratio (4 m-tall or less)	1		1	

[1] Lodgepole pine, unless otherwise noted.

In turn, variations in snow accumulation and melt patterns with year, with changes in forest cover, and over a watershed are assumed to be reflected in the spring hydrograph.

Many studies have attempted to quantify relationships between forest characteristics and snow accumulation or melt. Attempts to collate the literature are difficult, in part because of the diversity in forest types under which the research was conducted, but also because of the wide variation in measurement, analysis, and reporting techniques. In a coastal study, Hudson (2000) concluded that canopy height was a useful index to "recovery," as defined for snow accumulation and melt combined. He reported that canopy height accounted for 48% of the variation in the recovery index among stands. In a detailed review of the literature, only two studies were found that attempted to correlate snow melt with forest structure variables. Of these, only one provided comment regarding the proportion of the variation in melt explained by the individual canopy variables. Very few studies report the effects of forest regrowth and juvenile stand structure on snowpack processes. Two studies (Connaughton 1935; Hardy and Hansen-Bristow 1990) included juvenile stands similar to those found locally (Table 1).

Commonly, researchers have found that linking forest structure to snowpack processes is more successful at the stand level than at the plot level and for broad differences in stand characteristics rather than for smaller variations such as those attributable to varying stages of stand development. Rarely have multiple canopy variables been measured repeatedly over an extensive area or in diverse forest types in the same study.

STUDY AREA

This study was undertaken at two locations: Mayson Lake, approximately 50 km northwest of Kamloops; and Upper Penticton Creek, about 26 km northeast of Penticton. At Mayson Lake, four sites were surveyed. All sites were on level terrain at an elevation of 1200 m and adjacent to each other. One site was forested with a mature stand of Engelmann spruce, subalpine fir, and some lodgepole pine (spruce-fir). The second and third sites were reforested with 15-year-old lodgepole pine (pine). One of these two juvenile stands was thinned to approximately 1000 stems/ha and pruned to a height of 3 m. The fourth site was clearcut.

At Upper Penticton Creek, five sites were surveyed in two areas located approximately 5 km apart: 240 Creek and Dennis Creek. The study sites were: a clearcut and a mature lodgepole pine stand at 240 Creek; and a clearcut, a mature Engelmann spruce–subalpine fir stand, and a juvenile stand of Engelmann spruce and subalpine fir at Dennis Creek. All sites were on level terrain at 1600 m.

METHODS

Snow accumulation and melt were measured at 64 permanent sample points at each of the Mayson Lake and Upper Penticton Creek study sites during 1995, 1996, and 1997. The sample points at each site were spaced in a 15-m by 15-m grid pattern covering an area of approximately 1 ha. Snow measurements were made within a 1-m radius of the station marker using a standard Federal snow tube. Peak snow accumulation was represented by the April 1 SWE, and average melt rates were calculated over the period beginning on April 1 and ending on the date a zero value was recorded. SWE is the amount of liquid water that would result from melting a sample of snow, and is measured using a scale that converts the weight of a snow core to water equivalent. At Mayson Lake, snow measurements were made every 3–4 days during the melt period and every 2 weeks at Upper Penticton Creek.

The data collected during this study were analyzed as individual plots and as stand averages. Using each plot individually provided 576 examples of snow accumulation and melt under varying forest cover conditions including clearcut (384 examples under forest cover and 192 clearcut). The stand averages provided nine examples (six under forest cover and three clearcut).

Standardized ratios of SWE and melt rate were calculated by dividing individual forested plot and site-average data by the clearcut average for that location. For example, if the average SWE in the forest was 6 cm and that in the clearcut was 10 cm, then the ratio would be 0.6, meaning that 40% less water was measured in the forest. These ratios allow comparisons between areas with different snow regimes, including different study locations and years, as well as comparisons with results reported in the literature.

A detailed forest inventory was completed within 4-m-radius plots centred at each snow survey station. The inventory included variables describing the species mix, stem, and canopy. The species mix was thought to reflect general tree form and distribution. The stem descriptors were intended to represent stand structure, density, and stage of development. The canopy variables represented the depth, volume, and extent of foliage in the stand. Species, condition (live or snag), diameter outside bark at breast height (dbh; 1.3 m above ground), height, height to live crown, and crown radius were noted for each tree. Basal area, crown length, crown-base area, and crown volume were then calculated for each tree. Individual tree measurements were totalled or averaged, depending on the variable, to obtain values for each plot. The fifteen stand-structure variables summarized for each plot were:

- species
- total number of stems
- number of stems of lodgepole pine
- number of stems of Engelmann spruce and subalpine fir
- number of live stems
- number of snags
- average tree height
- total basal area
- average crown length
- average crown ratio (crown length relative to total tree height)
- crown-base area (estimated from the average crown radius measured in four directions)
- average crown length to base ratio
- total crown surface area
- total crown volume (an estimate based on crown-base area and crown length, assuming crown shape to be that conical, which does not account for overlap between crowns)
- crown closure (measured with a moosehorn)

All ratios of SWE and melt for each survey station and site were plotted against all forest structure variables to identify any possible relationships. Square root transformations were applied to the variables crown volume and basal area to linearize their relationships with the snowpack variables. Single and multiple linear regression techniques were used to identify statistical relationships between canopy and snowpack variables. Statistical significance for all tests was determined using $\alpha = 0.01$. Regression analyses were completed using SAS software (SAS Institute Inc. 1988). Residuals were plotted to visually evaluate the assumptions of normality and homogeneity of variance. The "best" models were selected based on comparisons of the coefficients of determination (r^2), standard errors of the estimate (SE_e), significance of the F values, and the residual plots. This study did not include true replicates; rather, the measurements were repeated over 3 years. Data for each year were analyzed separately, and each location represented a case study.

Note that it was not the intent of this study to present mathematical relationships between forest structure and snowpack variables, although from a forest-operations perspective this is tempting. It should be clear to the reader that the results presented here represent only six stands. Even though these six stands were selected because they appear to be typical of extensive forest cover types and each was intensively sampled, they do not represent a particularly broad range of conditions. The results of the data analyses presented here are intended to show those forest structure variables likely to be correlated to snow accumulation and melt in this region. In future, relationships may be derived from broader surveys focused on the key variables identified as part of this project.

Snow accumulation and average melt rates varied significantly during this study, both from site to site and from year to year. Detailed discussions of this variability can be found in Winkler (1999). The ratios of mature forest to open April 1 SWE ranged from 0.7 to 0.9. The largest differences between the forest and clearcut were observed where the predominant tree species were Engelmann spruce and subalpine fir (0.7 and 0.8) rather than lodgepole pine (0.9). The ratios of average melt rate under the forest compared to the open were 0.4 and 0.6 in the mature spruce-fir, 0.8 and 0.9 in the juvenile pine and 1 in the juvenile spruce-fir (Table 2). The results indicated some "recovery" at Mayson Lake and none at Upper Penticton Creek. The results obtained in this study are similar to those reported in the literature (Table 1).

The forest structure characteristics of each study stand are provided in Table 3. These data illustrate the differences in stem density, basal area, estimated crown volume, and crown closure between stands. At Mayson Lake, the mature spruce-fir stand had approximately 4400 stems/ha, the juvenile stand 2600 stems/ha (59% of the mature stand), and the thinned stand 1000 stems/ha (23% of the mature stand). The basal area of the juvenile thinned and juvenile pine stands was 13 and 19% of that in the mature spruce-fir, respectively, and the estimated crown volume was 34 and 58% of the mature. Average crown closure was 21 and 28% in the juvenile thinned and juvenile stands and 54% in the mature forest. At Upper Penticton Creek, crown closure measured with the moosehorn was 0% in the juvenile spruce-fir stand and 44% in the mature. Stand basal area in the juvenile stand was 12% of that in the mature spruce-fir. Stocking in the juvenile stand was as high as 78% of that in the mature stand: 3600 stems/ha compared to 4600 stems/ha.

All stand-structure variables were regressed against standardized April 1 SWE and standardized average melt rates, first using each plot as an individual observation and then using site averages (Table 4). The results show that, at Mayson Lake and Upper Penticton Creek, crown length, crown volume,

TABLE 2 *Average April 1 snow water equivalent (SWE), melt rates, and standardized ratios of forest (F) to open (O) SWE and melt at Mayson Lake and Upper Penticton Creek*

Location and forest cover	Apr 1 SWE (cm)	Apr 1 SWE F:O	Melt Rate (cm d^{-1})	Melt Rate F:O
Mayson Lake				
Clearcut	22		0.99	
Juvenile thinned pine	19	0.9	0.92	0.9
Juvenile pine	19	0.8	0.82	0.8
Mature spruce-fir	15	0.7	0.41	0.4
Upper Penticton Creek				
Clearcut	37		0.72	
Mature pine	33	0.9	0.52	0.7
Clearcut	31		0.65	
Mature spruce-fir	24	0.8	0.40	0.6
Juvenile spruce-fir	32	1	0.66	1

TABLE 3 *A summary of stand characteristics at the Mayson Lake and Upper Penticton Creek study sites (n=64 at all sites)*

	Mayson Lake			**Upper Penticton Creek**		
Forest-structure variable	**Juvenile thinned mean (SD)**	**Juvenile mean (SD)**	**Mature forest mean (SD)**	**Mature forest mean (SD)**	**Mature forest mean (SD)**	**Juvenile mean (SD)**
Tree species	pine	pine, spruce-fir	spruce-fir, pine	pine	spruce-fir	spruce-fir, pine
Total stems/ha	1000 (400)	2600 (1600)	4400 (1400)	6400 (1600)	4600 (1800)	3600 (2200)
Stems of lodgepole pine/ha	800 (400)	1400 (800)	600 (400)	3600 (1200)	0 (200)	400 (600)
Stems of spruce-subalpine fir/ha	200 (200)	1000 (1400)	3000 (1200)	400 (1000)	3800 (1600)	3000 (2200)
Live stems/ha	1000 (400)	2600 (1600)	3600 (1400)	4000 (1000)	3800 (1800)	3400 (2200)
Snags/ha	<200	<200	800 (600)	2400 (1200)	600 (600)	<200
Average tree height (m)	6.4 (1.5)	4.5 (1.4)	10.1 (3.4)	14.7 (2.5)	6.6 (2.3)	2.8 (0.6)
Total basal area (m^2/ha)	8 (10)	12 (6)	62 (24)	58 (12)	48 (22)	6 (6)
Average crown length (m)	3.9 (0.9)	3.8 (1.2)	5.2 (1.5)	4.0 (0.9)	4.1 (1.4)	2.7 (0.6)
Average crown ratio (m/m)	0.6 (0.1)	0.8 (0.1)	0.5 (0.1)	0.3 (0.1)	0.6 (0.1)	0.9 (0)
Total crown base area (m^2/ha)	4160 (2100)	5860 (2340)	7420 (2800)	4240 (1380)	8000 (2600)	5440 (3140)
Average height to base ratio (m/m^2)	1.8 (0.4)	2.6 (1.1)	3.4 (0.8)	3.7 (0.9)	2.8 (0.7)	2.0 (0.3)
Total crown surface area (m^2/ha)	3060 (1400)	2100 (1320)	2540 (1040)	1440 (440)	2060 (1120)	1180 (400)
Total crown volume (m^3/ha)	6600 (3660)	11,380 (5180)	19,500 (8760)	6440 (2560)	17,760 (6980)	6820 (4960)
Crown closure (%)	21 (30)	28 (31)	54 (27)	40 (20)	44 (35)	0 (0)

TABLE 4 *A summary of the proportion of the variation in standardized April 1 SWE and standardized average snow melt rates explained by the forest structure variables measured at Mayson Lake and Upper Penticton Creek*

	Among plots (n=384)			Among sites (n=6)		
Forest-structure variable	**1995**	**1996**	**1997**	**1995**	**1996**	**1997**
vs. standardized April 1 swe						
Total stems	0	0	0.01	0	0	0.04
Stems of pine	0	0.01	0	0.03	0.08	0.05
Stems of spruce and fir	0	0.01	0.01	0.03	0.08	0.12
Live stems	0	0	0	0	0	0.05
Snags	0	0	0.01	0	0	0.02
Average tree height (m)	0.03	0.04	0.07	0.09	0.12	0.13
Basal area (m^2/ha)	0.09	0.14	0.17	0.30	0.42	0.50
Average crown length (m)	0.12	0.15	0.18	0.87	0.85	0.79
Average crown ratio (m/m)	0.03	0.06	0.07	0.10	0.19	0.19
Total crown base area (m^2/ha)	0.08	0.11	0.11	0.37	0.39	0.51
Total crown volume (m^3/ha)	0.17	0.19	0.22	0.66	0.69	0.78
Crown closure (%)	0.28	0.28	0.26	0.68	0.75	0.84
Square root of crown volume	0.19	0.21	0.25	0.67	0.69	0.80
vs. standardized snow melt						
Total stems	0.13	0.12	0.13	0.35	0.33	0.32
Stems of pine	0	0	0	0	0	0.02
Stems of spruce and fir	0.06	0.06	0.13	0.14	0.18	0.35
Live stems	0.09	0.07	0.11	0.3	0.32	0.4
Snags	0.11	0.09	0.06	0.26	0.21	0.12
Average tree height (m)	0.20	0.17	0.11	0.44	0.35	0.19
Basal area (m^2/ha)	0.38	0.40	0.39	0.89	0.85	0.75
Average crown length(m)	0.13	0.12	0.15	0.74	0.74	0.58
Average crown ratio (m/m)	0.21	0.17	0.11	0.40	0.31	0.17
Total crown base area (m^2/ha)	0.06	0.07	0.15	0.34	0.46	0.66
Total crown volume (m^3/ha)	0.17	0.20	0.31	0.56	0.69	0.81
Crown closure (%)	0.17	0.15	0.19	0.83	0.88	0.78
Square root of basal area	0.42	0.41	0.44	0.86	0.83	0.74

and canopy density each explain a larger proportion of the variability in April 1 SWE than do the other forest structure variables measured. However, none of the variables explained more than one-third of the variability among plots, indicating that other factors may have a larger influence or that the processes affecting April 1 SWE occur over a larger area than that represented by the 0.005-ha plots. Over the 3 years, crown length explained 12–18% of the variability in standardized April 1 SWE among plots, the square root of crown volume 19–25%, and crown closure 26–28% of the variability.

At the stand scale, depending on the year, crown length, crown volume, and crown closure explained 79–87%, 67–80%, and 68 to 84% of the variability in standardized April 1 SWE, respectively. Of the three stand-structure variables, crown length was thought to be the most useful. When crown closure and standardized April 1 SWE were plotted, the wide scatter of points did not indicate a clear relationship between these variables. From a practical perspective, crown length is much easier to measure than crown volume.

The square root of basal area explained the greatest proportion of the variability in standardized snow melt, at up to 44% of that among plots. At the stand scale, this variable explained 74–86% of the variability in standardized melt. Multi-variate models were also explored. No improvement in the prediction of either standardized SWE or snow melt was achieved using multiple variables rather than the single variables just described.

In contrast, average tree height explained only up to 7% of the variability in standardized April 1 SWE among plots, and up to 20% of that in melt. At the stand scale, tree height still explained only up to 14 and 44% of the variability in standardized April 1 SWE and melt, respectively. Table 5 provides a summary of recovery for the tree heights of the juvenile study stands expected according to current guidelines (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) and from the snow survey data. Problems associated with oversimplification of complex processes are illustrated by the results.

Table 5 shows large annual variability in recovery calculated using the guidebook (B.C. Ministry of Forests and B.C. Ministry of Environment 1999), suggesting that the formula may not be appropriate for the comparison of multiple locations. When recovery is averaged over the three study years, the guidebook values approximate recovery measured as April 1 SWE, but overestimate that measured as average melt. This likely reflects the increased interception capabilities of taller trees, on average, but does not provide an indication of a stand's ability to shade the surface of the snowpack.

A preliminary relationship between crown length and standardized April 1 SWE is shown in Figure 1, along with the field measurements at the six study sites in each of the 3 survey years. If these data are indicative of a broader range of crown lengths than those measured, they suggest that once trees in stands similar to those studied are taller than 2.8 m, a 10% decrease in April 1 SWE could be expected under the forest canopy compared to that in the open for every 0.6- to 0.7-m increase in crown length.

The preliminary relationship between the square root of basal area and standardized average melt rate is shown in Figure 2. Again, only portions of the range in basal area were sampled in this study. The relationship shown suggests that, for an increase in the square root of basal area/ha of 1.2–1.3, a

TABLE 5 *Recovery as provided in, and calculated according to, the* Forest Practices Code of British Columbia, Coastal Watershed Assessment Procedure Guidebook (CWAP), Interior Watershed Assessment Procedure Guidebook (IWAP) *(B.C. Ministry of Forests and B.C. Ministry of Environment 1999) for the juvenile stands at Mayson Lake and Upper Penticton Creek*

Stand	Tree height (m)	Guidebook recovery (%)	Recovery based on measured SWE			Recovery based on measured melt		
			1995	1996	1997	1995	1996	1997
Juvenile pine	4.5	25	44	50	28	10	18	0
Juvenile thinned pine	6.4	50	67	33	43	12	35	32
Juvenile spruce-fir	2.8	0	14	0	0	4	0	6

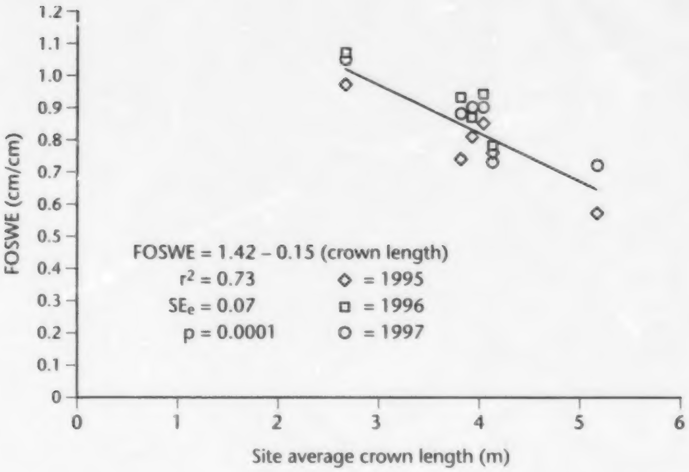

FIGURE 1 *A preliminary relationship between crown length and standardized April 1 SWE, and field measurements at Mayson Lake and Upper Penticton Creek.*

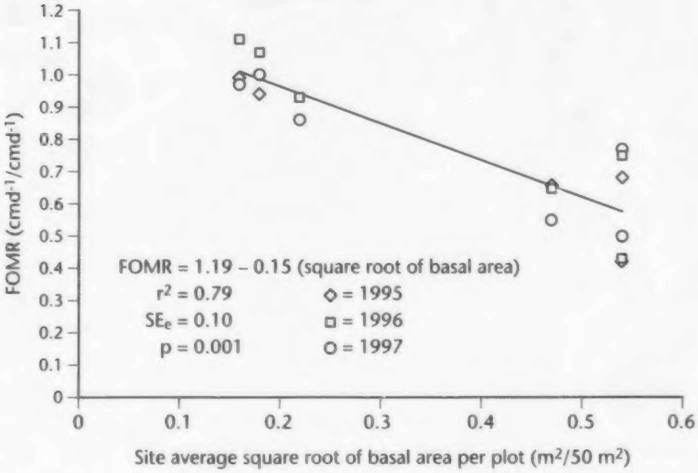

FIGURE 2 *A preliminary relationship between the square root of stand basal area and standardized average melt rate, and field measurements at Mayson Lake and Upper Penticton Creek.*

10% decrease in melt rate under the forest canopy relative to the open could be expected under conditions similar to those at the study sites. Note that the square root of basal area cannot simply be converted to basal area/ha to specify corresponding rates of decrease in melt, since the relationship is not linear.

As is clear from the limited range of survey stands shown in Figures 1 and 2, additional data from diverse forest cover types are required to test these initial findings and to confirm that the forest structure variables identified here, either alone or in combination with others, are predictive of the variability in snowpack characteristics over the region.

CONCLUSIONS

Stand variables such as crown length and basal area may be useful operationally to evaluate potential changes in maximum snow accumulation and melt following logging and with forest regrowth. Crown length explained 79–87% of the variability in April 1 SWE among the study stands, and the square root of basal area explained 74%–86% of the variation in snow melt. Both variables explained a greater proportion of the variability in forest to open April 1 SWE and average melt rate among stands than did tree height. Incorporating stand-structure variables representative of snow interception and shading under varying forest cover conditions into the current assessment procedure would provide a more hydrologically sound tool for estimating hydrologic recovery.

To validate and improve upon the preliminary indices described here, similar data from the Nelson Forest Region will be incorporated into the study, thus providing information about a broader geographic area and diversity of stand types.[1] Work to incorporate meteorological variables into the analysis is also under way.

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Snowline Pattern during the Melt Season: Evaluation of the H60 Concept

DAVID R. GLUNS

ABSTRACT

The H60 concept refers to the elevation of the snowline when the upper 60% of a watershed is covered in snow. Timber harvesting in this "snow zone" is thought to have a greater influence on peak flows due to changes in snow accumulation and snowmelt when the forest canopy is removed. To account for this influence, the Interior Watershed Assessment Procedure provides a weighting mechanism for harvesting proposed in this zone. To test this principle, a 5-year study to look at snowlines and streamflow was undertaken. At the time of peak flow, on average, it was found that approximately 65% of a watershed was covered in snow. The H60 concept is valid for watersheds in the southern interior of British Columbia as a tool for evaluating forest-harvesting proposals.

INTRODUCTION

Watershed assessments are used to assess the potential impact of proposed timber-harvesting activities on streamflows, suspended sediment, landslides, and channel stability within a drainage basin. Part of the assessment of streamflows is evaluating peak flow change. Changes in peak flows as a result of forest development have received considerable attention and study, and the findings are controversial (Jones and Grant 1996; Thomas and Megahan 1998.) In the Interior of British Columbia, the majority of peak flows are generated through snowmelt or rain-on-snow through the later part of the melt season. These and other causes of peak flows are described by MacDonald and Hoffman (1995). Local research on the effects of forest removal on the snowpack has shown an increase in the amount of snow water equivalent (SWE) and an increase in melt rates (Toews and Gluns 1986). This may have a potential influence on runoff in terms of an earlier peak or a higher peak, depending upon the elevation, aspect, and extent of the harvesting. Recognizing that a change in the snowpack can influence streamflow, it was necessary to come up with an indicator for peak flows that is easily measured.

Currently, the Interior Watershed Assessment Procedure (IWAP) uses equivalent clearcut area (ECA) and road density as a surrogate to evaluate peak-flow concerns. ECA refers to areas that have been disturbed (i.e., harvested, cleared, or burned). It is also a means to keep track of areas that are partially cut or areas that are regenerating. At present, assumptions for ECA values take into account regenerating stands based on heights of 3, 6, and 9 m. Assumptions for ECA calculations are listed in the *Interior Watershed Assessment Procedure Guidebook* (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). In assessing watersheds, it is recognized that differential melt within a watershed accounts for elevational variability in runoff-generating mechanisms. The snowpack generally increases in SWE with elevation. This increase also translates into higher melt rates at elevation due to the onset of warmer temperatures and the increased amount of water available in the snowpack. At any given elevation, when the snow is consistently covering the watershed, this is referred to as the snowline. When the watershed is experiencing rapid melt, and streams are peaking, the snowline at the time is the one of interest. In the original version of the IWAP this was described as the H60 line—the elevation above which 60% of the watershed lies. The area above this line is considered to be the major source area for contributing to peak flows. Forest removal in this "snow zone" is assumed to affect snow accumulation/melt and subsequent runoff by increasing the amount of SWE and increasing the melt rates (Toews and Gluns 1986).

The basis of the H60 concept comes in part from a study by Garstka et al. (1958) on St. Louis Creek in Colorado. Their findings suggest that streamflow as a result of snowmelt begins to rise when only 10% of the basin is free of snow. During this time, streamflow went from 0.255 m^3/sec (baseflow) to 1.18 m^3/sec. When the basin was 30% bare of snow, streamflow had increased to about 3.82 m^3/sec. By the time the steamflow had reached peak flow (8.30 m^3/sec) the basin was 55% bare of snow. The graph in Figure 1 shows the

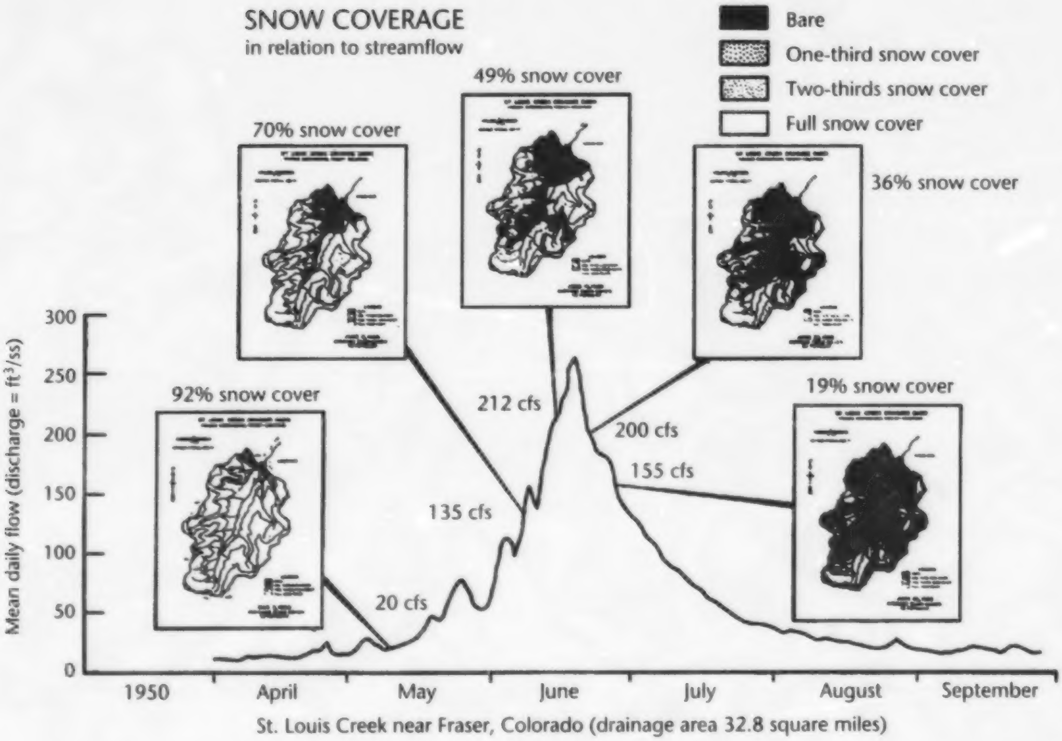

FIGURE 1 *Graphical results of a study by Garstka et al. (1958) that illustrate the relationship between streamflow and snow cover in a basin in Colorado.*

results of the study by Garstka et al. (1958) at St. Louis Creek near Fraser, Colorado where they looked at the percentage of the watershed covered in snow with respect to streamflow. This graph forms the basis of the H60 line concept in the IWAP and provides a conservative approach to identifying the snow zone. Based on the findings of Garstka et al. (1958), an H45 would represent the snowline at peak flow.

It is clear in reviewing the Colorado study that the assumption of the 60% snowline for interior watersheds of British Columbia is more an "educated guess" than based on any local information. There are no other known studies that have reported on aerial snow cover and streamflow for small-forested watersheds in British Columbia.

Most of the work done with aerial snow coverage has been with satellite and has proved effective for broad-scale studies. For discussion of the technology, see Pomeroy and Gray (1995). While that technology exists, for the purpose of this study, the cost, timing, and resolution of utilizing satellite imagery was considered beyond the realm of what would be effective in meeting our objective.

This project was initiated in an attempt to verify the concept of area-based snow coverage and streamflow. Since the current state of knowledge was limited to an early study with more of a continental climate, there was a need to ensure that the assumptions built into the guidebooks were valid.

The objective of this study was to evaluate the H60 line (60% snow coverage) for applicability in the watersheds of the interior of British Columbia. This study was also to provide information on the utility of snowlines as a weighting factor for evaluating forest harvesting impacts. Furthermore, the study provides snow cover information as a supplement to the climate and snow monitoring in the West Arm Demonstration Forest. This included the measurement of SWE at representive elevations in the watershed during the accumulation and melt season.

METHODS

The study took place in the West Arm Demonstration Forest (WADF) in the Redfish and Laird creek drainages. The WADF is located 30 km east of Nelson (Figure 2). The Demonstration Forest is described by Crampton et al. (1992) and has many components to the project. The two watersheds were chosen because they are both gauged by the Water Survey of Canada, with Redfish having some historic streamflow data from 1967 to 1986. Area-elevations of the two drainages are presented in Figure 3. Laird Creek has a higher proportion of alpine land than Redfish Creek, but the H60 line is about the same for both at 1750 m. Both watersheds have a range of forest cover types, from cedar-hemlock to subalpine fir. They represent drainages typical of those having forest-harvesting potential in the southeastern region of British Columbia. At present, the Redfish watershed has had some harvesting, and future harvesting is planned. The Redfish watershed also has a series of climate and snow-monitoring stations located at various elevations, from valley bottom to alpine. Additionally, both watersheds are located close to Nelson, thereby minimizing travel time, which was of a tremendous benefit in collecting the data.

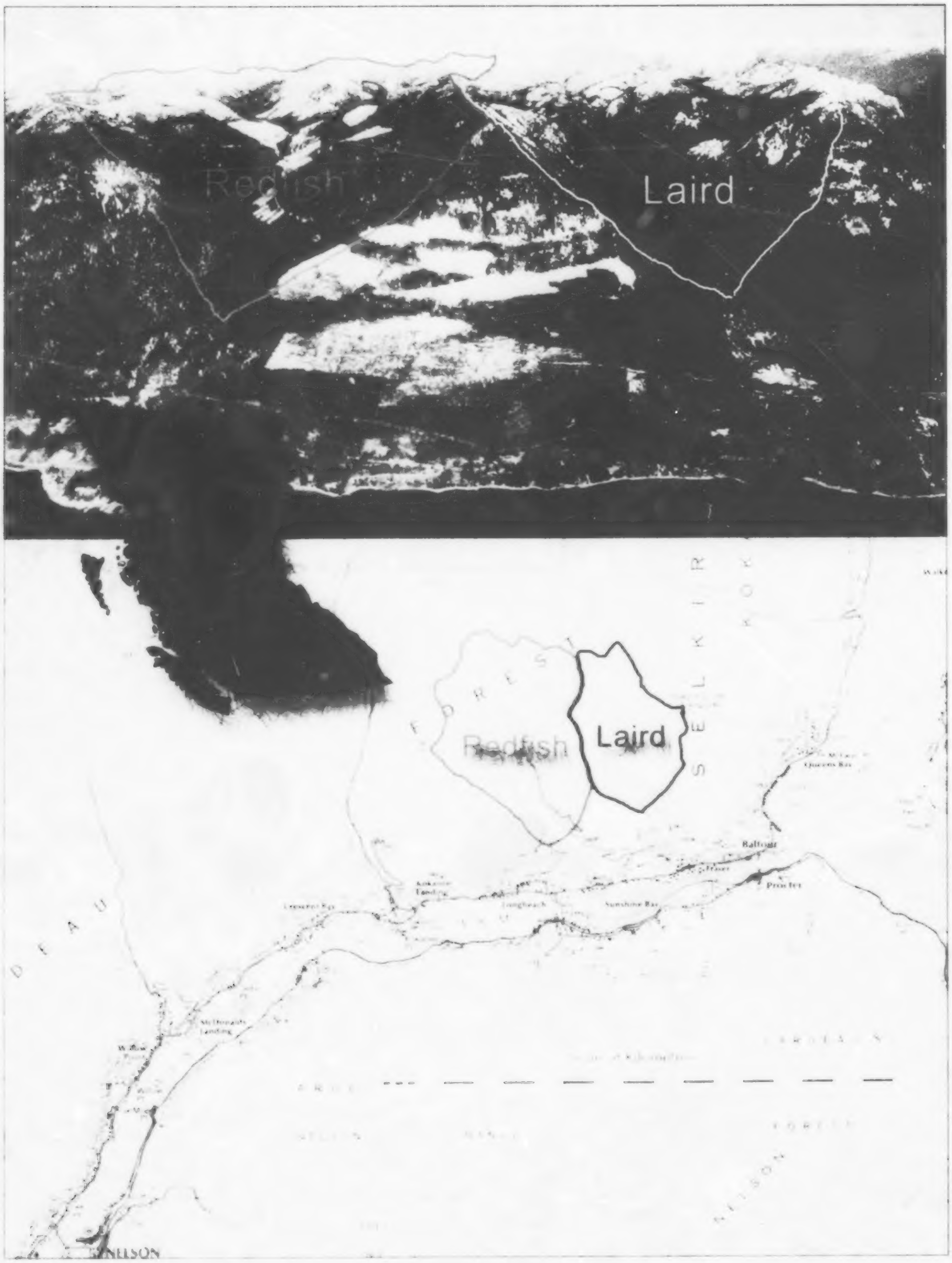

FIGURE 2 *Location of the Redfish and Laird creek watersheds near Nelson, in southeastern British Columbia.*

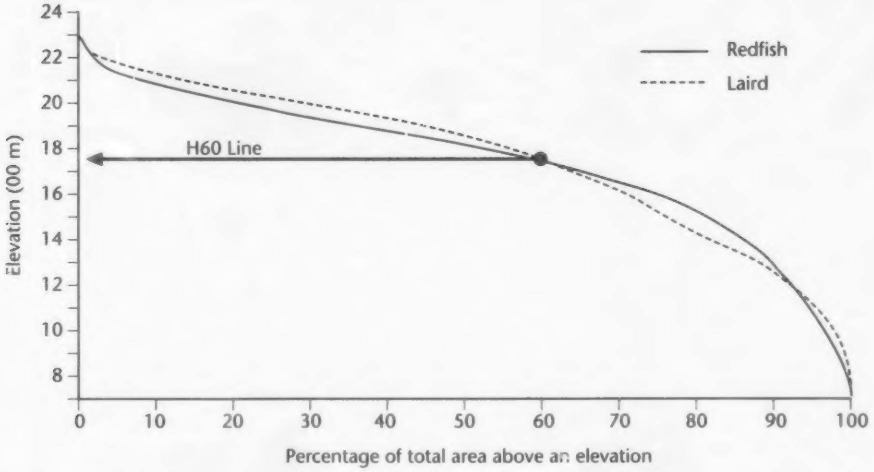

FIGURE 3 *Area-elevation curves for Redfish and Laird creek watersheds.*

To measure snow cover during the snowmelt period on each of the watersheds, it was necessary to have quick access to carry out the survey when the weather was co-operating. One of the limitations of using satellite images is that they are available only on a set basis (i.e., every 18 days), and if the drainage is cloud covered then there is no image available. Because melt can be rapid and unpredictable, it is possible to miss some key dates using that method. It was decided that the most cost-effective and efficient means to obtain snow cover data was to fly each drainage with a fixed-wing aircraft. A Cessna 172, with its overhead wings, provided good visibility for obtaining the necessary information. Additionally, with an aircraft based in Nelson, the cost of operating each survey was reasonable, and researchers could be airborne in a short time.

Snow disappearance was recorded using conventional photography (i.e., both a 35-mm still camera and a high-8 video camera) on regular flights over the two watersheds. The recording was monthly until rapid melt was noticed, and then recording switched to weekly. However, due to the mountain weather, this was not always practical, and flights were weather-dependent. The survey flights were tied in closely with the snow surveys carried out on the ground.

Photographs for each flight where analyzed by marking on the photograph the approximate boundary of the snowline by distinguishing between snow cover and bare ground. At the interface between snow and bare ground this required a degree of interpretation. Often, small patches of snow-free zones were balanced with areas that had snow, as the areas involved were not large enough to map. The interpretation of the line between snow and snow-free was done by one person so that it would be consistent from year to year. All lines were checked by another interpreter to ensure interpretation accuracy. Where necessary, to assist in the interpretation, researchers referred to the video shot on each flight.

The interpreted lines were transferred from the 36–72 oblique 10 × 15 cm (4 × 6 inch) photographs taken on each flight to an othophotographic base of both the Redfish and Laird watersheds. The snowlines were placed on the base as an overlay with the aid of ArcView.

The program had the ability to zoom into different areas and thus allow for a better placement of the snowlines. Snowlines were then analyzed directly to provide snow cover by survey date and by year. Snow-cover data were then analyzed in conjunction with the Water Survey of Canada (WSC) streamflow records for each watershed. Primary analysis consisted of plotting the snow-cover depletion curve with streamflow to assess the relationship between the two. The objective was to define the snow coverage at which peak flow occurs. This was carried out for each year and for the mean of all 5 years to take into account the year-to-year variability.

RESULTS AND DISCUSSION

Snowline surveys were carried out over a 5-year period. In Figure 4, these dates are displayed visually, with the WSC streamflow data that were collected, to provide an indication of aerial coverage during the snowmelt period and the yearly runoff patterns. In all years, snowmelt peaks were covered by snowline surveys. Streamflow magnitudes during this 5-year period were not unusual, and when compared with the 20-year historic values, were within the maximum and minimum recorded for Redfish Creek.

A visual representation of each snowline for 1996 is presented in Figure 5. This shows how the lines appeared on the ArcView display window following interpretation from the oblique aerial photos.

From this snow coverage, a snow-depletion curve was constructed and plotted against streamflow for each of the 5 years of data collection. The result of this analysis shows that there was a consistent melt pattern from year to year, although there were year-to-year variations. These snow-depletion curves were then averaged for the 5-year study period and analyzed with the average 5-year streamflow over the same period. The summary of the 5 years is presented in Figure 6 for Redfish Creek, and in Figure 7 for Laird Creek.

On both watersheds, the 5-year average peak streamflow occurred with about 65% of the basin still snow-covered. This value is close to the suggested 60% (H60 concept) in the initial IWAP. Streamflow started to rise when as little as 10% of the area of the watersheds was void of snow, and rose rapidly as the lower third of the basin melted out. Ground-based snow surveys were able to confirm that melt was occurring at higher elevations as well. Figure 8 shows the streamflow response to snowmelt at various elevations in the watershed. These data are based on a 5-year average for the watershed. This indicates that the snowmelt in the middle third of the drainage is critical during the development of peak flows. Snow survey and snow pillow records from a station in the alpine region of the drainage showed the snowpack starting to lose water as the middle third of the basin is undergoing rapid melt. The response of streamflow to melting in the watershed is illustrated in a series of graphs in Figure 9 for the 1996 snowmelt season. These results indicate that, in the middle portion of the basin, the differences in snow accumulation and melt arising from forest removal could be important in the de-synchronization and generation of peak flows.

The pattern of watershed snowmelt and the resulting streamflow observed in this study demonstrates some important points for this region. Peak streamflow magnitude and timing can be variable and are not as easily predictable as the colder continental climate upon which the concept of

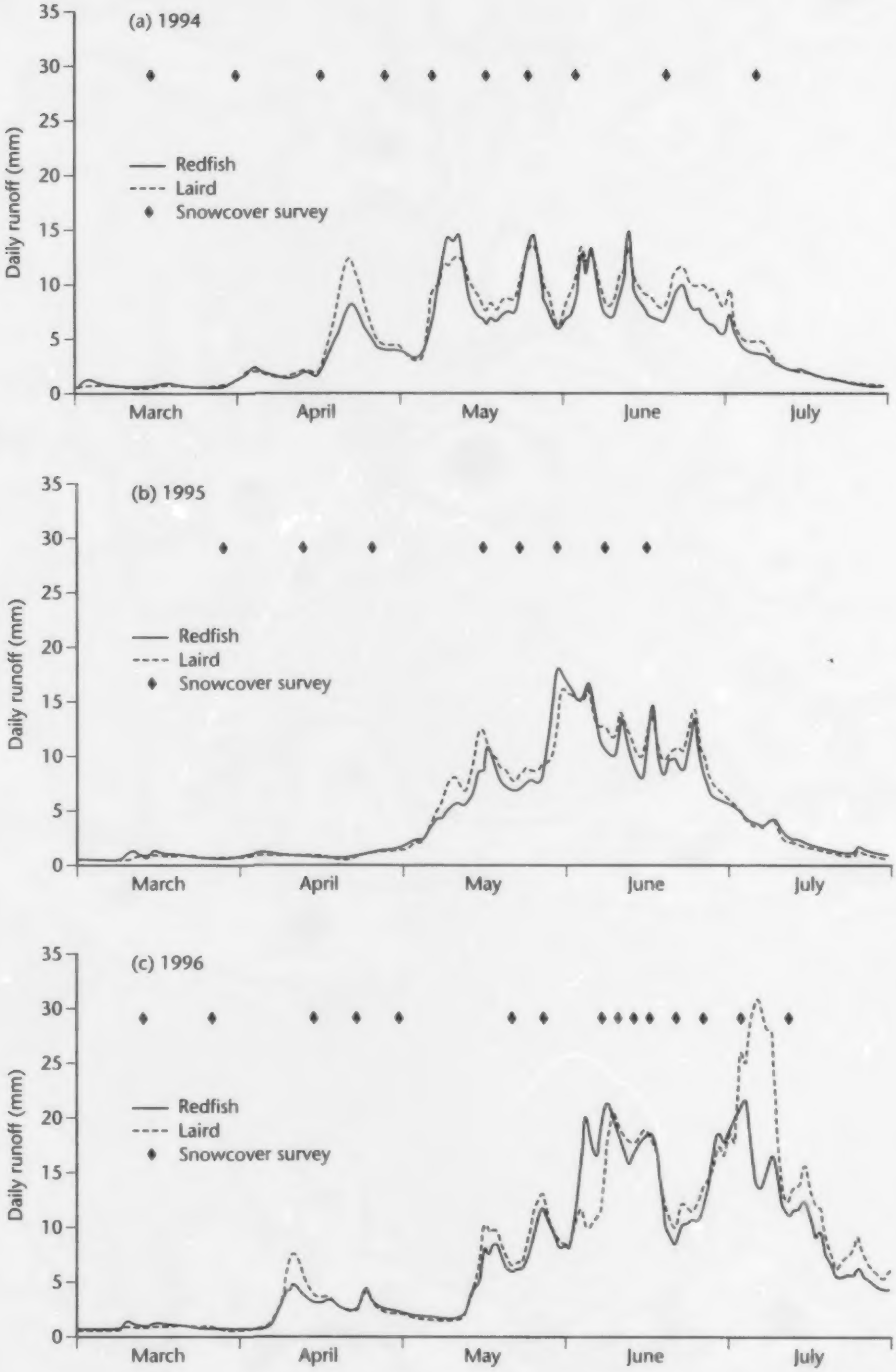

FIGURE 4 *Five years of hydrographs for both Redfish and Laird creeks. The timing of snowline flights is indicated.*

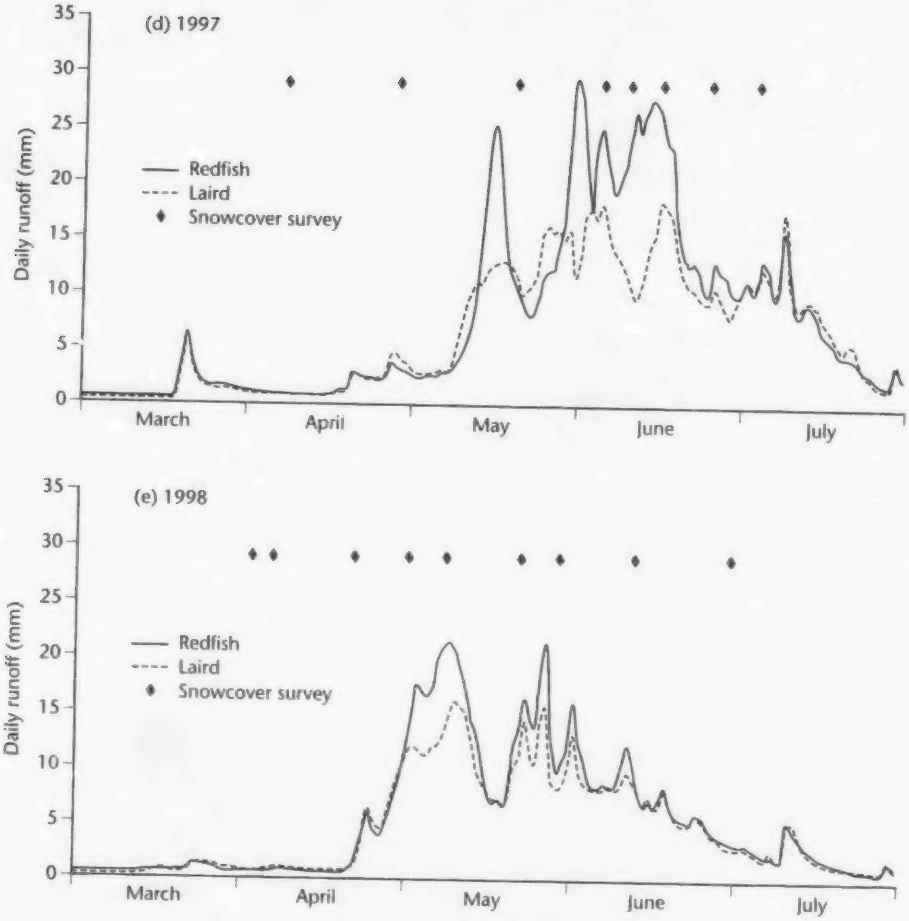

FIGURE 4 *Continued*

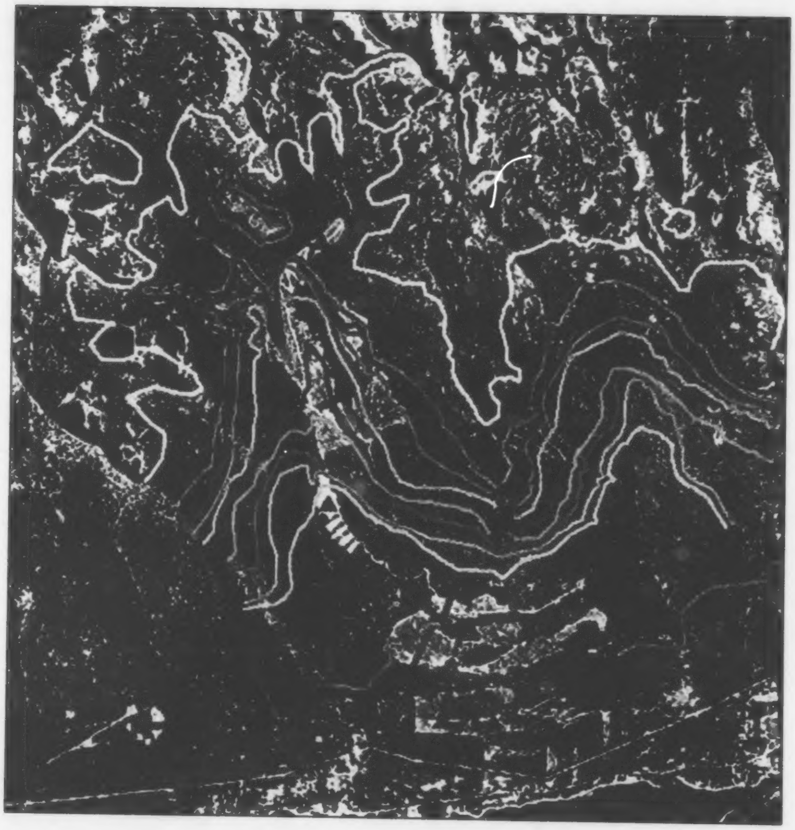

FIGURE 5 *Snowlines for 1996 as seen on the ArcView display after interpretation from oblique photos of snow cover.*

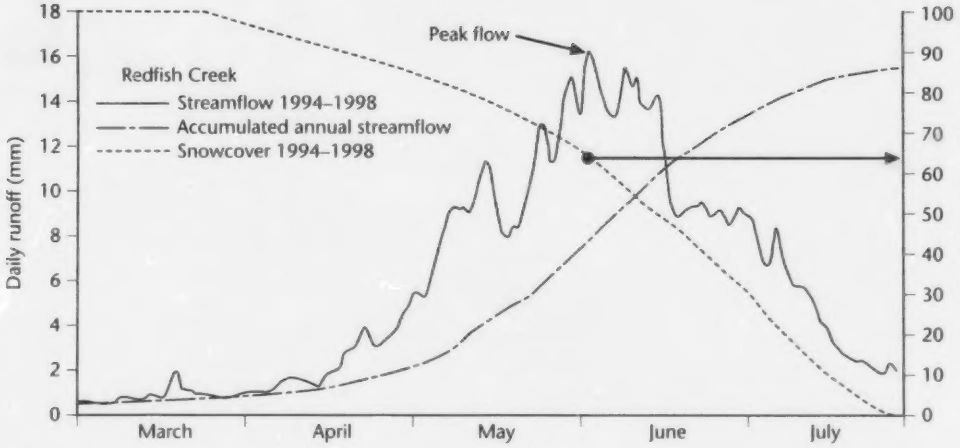

FIGURE 6 *Average 5-year snow cover depletion curve and streamflow hydrograph for Redfish watershed.*

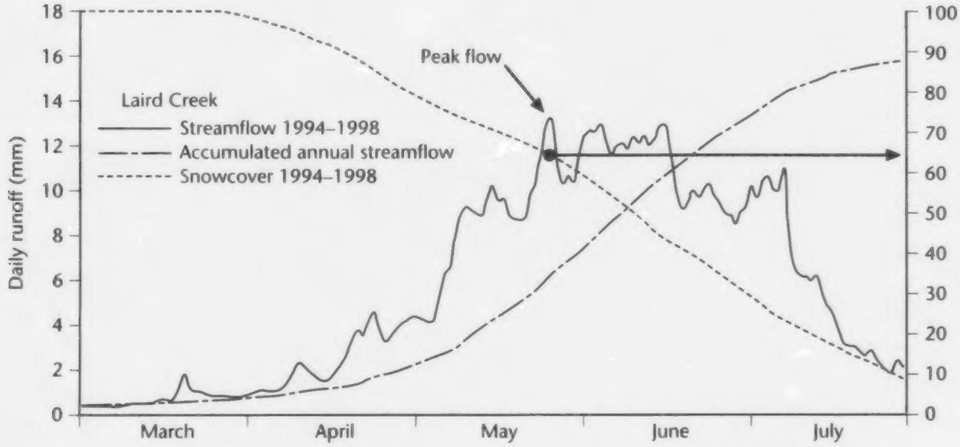

FIGURE 7 *Average 5-year snow cover depletion curve and streamflow hydrograph for Laird watershed.*

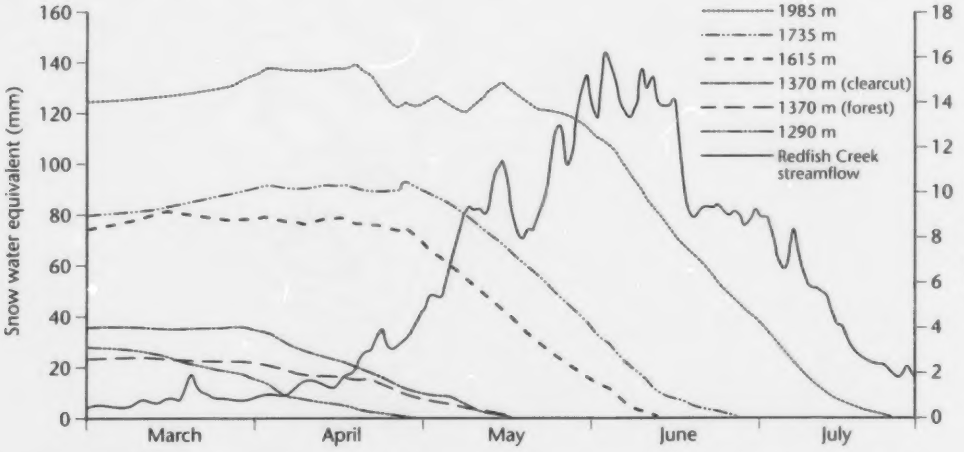

FIGURE 8 *Response of Redfish Creek to snowmelt from various elevations based on a 5-year averaging period.*

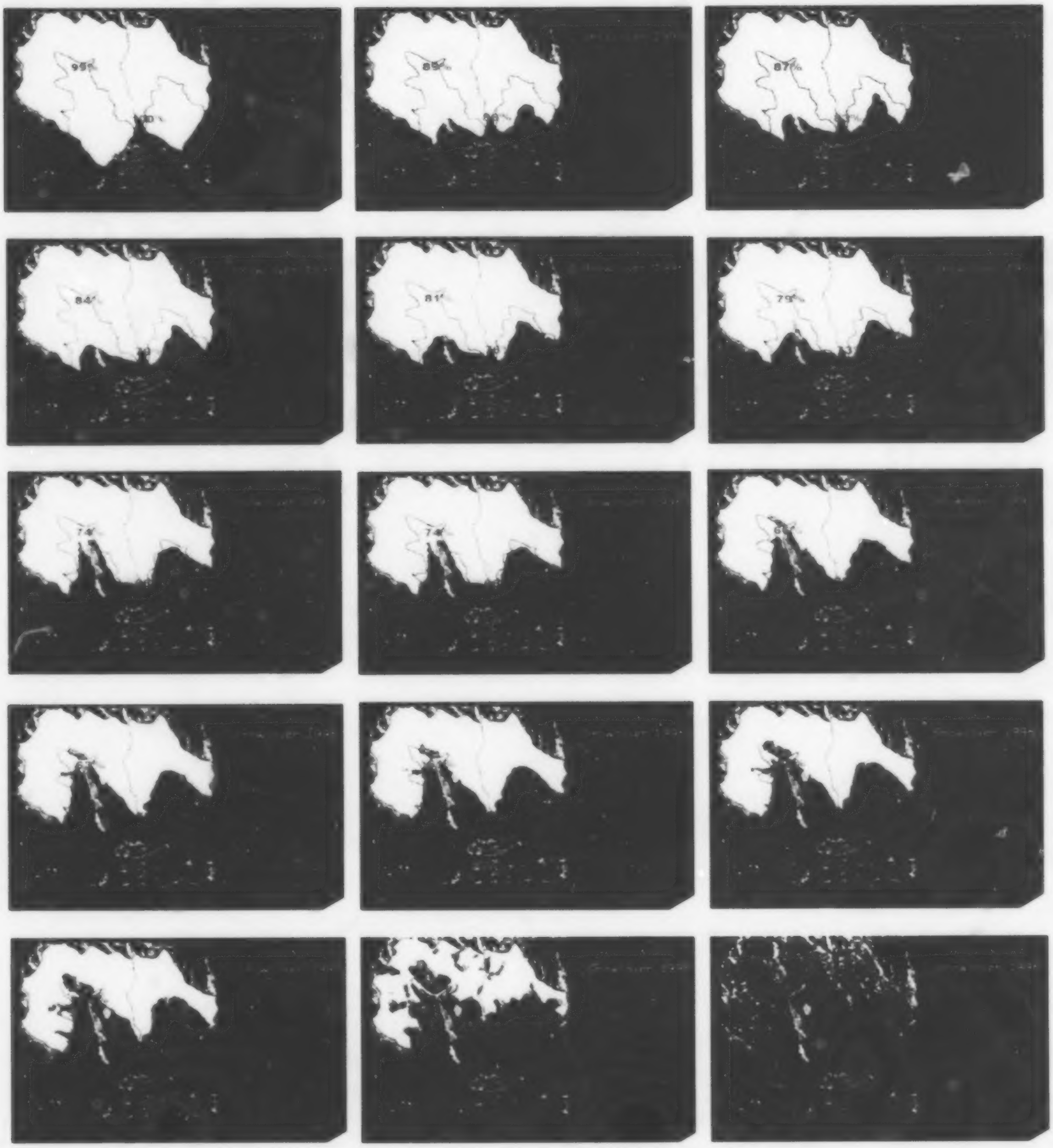

FIGURE 9 *Snow cover during the 1996 snowmelt season and the corresponding streamflow on each sampling date. The blue line on the airphoto indicates the H60 line for each of the watersheds.*

snowlines and streamflow are based. The runoff is highly dependent on the climatic events of the season and it could be solar-radiation driven, or influenced by a rain-on-melting-snow event. The result is that in some years several peaks can be seen in the annual hydrograph, with several peaks of equal magnitude. For example, the 1996 runoff year had peaks of similar magnitude being separated by 26 days. On the contrary, continental climate hydrographs, as shown in Garstka et al. (1958), tend to have one main peak.

The role of aspect and elevation is also significant in the melt pattern. It was found that the pattern of snowcover was consistent from year to year. The snowline was not found to follow a specific contour at any one time, but was variable, depending on the aspect and position in the watershed. The snowline tended to be much higher on the south-facing valley walls near the outlet of the watershed and persisted longer in lower elevations along the main drainage channel.

Whitaker et al. (2001) analyzed the impacts of forest harvesting on streamflow by modelling melt from several zones in the watershed. These were H80–H100 (lowest forest zone), H60–H80 (middle forest zone), H40–H60 (upper forest zone), and H0–H40 (alpine zone). They found that harvesting the lowest zone had no effect on peak flows, whereas harvesting in the middle zone showed some increase, depending on the amount of timber removal. The greatest effects were seen while harvesting in the upper forest zone. This lends credibility to the concerns about harvesting in the upper zone (above H60), and supports the concept of weighting timber harvesting proposals in this zone.

The applicability of using the H60 concept in other watersheds in the interior is dependent upon the characteristics of the drainage and the runoff pattern. Results from this study can be applied to watersheds with snow-dominated runoff, a broad range of elevations, and a general increase in SWE with elevation. Without further verification, the results will be limited in watersheds with a narrow range of elevations (i.e., a drainage with a plateau area encompassing the upper portion of the drainage basin), or where differences in snow accumulation between upper and lower elevations is generally low.

What these data show is that the generation of peak flow is concentrated when snow in the 40–80% snow coverage range is undergoing rapid melt. The 5-year study shows that the H60 in reality is H65 for the watersheds looked at. This difference is not significant and may be within the error of interpretation. This finding does not warrant a change in the H number.

The H60 concept is valid in weighting upper-elevation harvesting in a watershed context and is important when it comes to planning timber-harvesting activities in the snow zone.

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Retrospective Analysis of the Effects of Harvesting on Peak Flow in Southeastern British Columbia

B. E. MCFARLANE

ABSTRACT

The paired-watershed approach was used retrospectively to identify control and treatment watershed pairs from 66 gauged watersheds in southeastern British Columbia. Peak-flow and forest-harvest data were analyzed using both graphical and statistical tools, and results were compared with accepted theory to determine consistency. Study findings indicated that while specific changes in peak flow could be detected, the relationship of these changes to the treatment could not be substantiated. Possible sources of error were discussed, and several considerations for better design of paired-watershed experiments were recommended.

INTRODUCTION

Over the past few decades, numerous studies relating the effects of forest harvesting to peak-flow changes have been published in the scientific literature (Scherer 2001, this publication). One of the most credible experiments for determining such changes in peak flow is the paired-watershed method, wherein treatment and control watersheds are calibrated prior to treatment. The subsequent differences between expected and measured stream-flow response is a measurement of the treatment effect. Normally, paired watersheds are identified prior to treatment and the harvesting is conducted with the experiment in mind. In some cases, the paired-watershed method can be retrospectively applied to suitable watershed pairs, if sufficient stream-flow data exist in both the pre- and post-treatment periods. Jones and Grant (1996) used this approach to detect peak-flow changes in rain-dominated watersheds of coastal Oregon. In this study, 66 gauged watersheds in southeastern British Columbia were examined to find watershed pairs that could be used to detect changes in peak flow and potential correlation with forest harvesting.

SELECTING WATERSHED PAIRS

Watersheds were first compared for similarities in 13 geomorphological indicators, including measures of watershed area, drainage density, main channel gradient, maximum basin elevation, steep-land area, and lake area. These watershed characteristics, which had been derived from 1:50 000 topographic forest-cover maps, were provided by the B.C. Ministry of Forests. Data were statistically compared for watershed similarity using algorithms developed by Cheong (1995), and candidate watersheds were selected for low values of dissimilarity. Assumptions about climatic similarity were based on watershed elevations, snowpack data, and location by latitude and orientation. To reduce the potential for spatial variability, only those watersheds having areas in the order of 10 000 ha or less were examined further. Following this selection process, candidate watershed pairs were screened for peak-flow data that were concurrent between control and treatment watersheds, had cumulative forest harvesting over the period of study near or above 20%, and, therefore, met the basic requirements of a paired-watershed study. Separation of distinct calibration and treatment periods became evident with application of statistics to peak-flow data, as explained below.

Two watershed pairs—Anderson and Sullivan creeks, and Sinclair and Windermere creeks—were finally chosen as case studies for statistical analysis of peak flow (Figure 1). Several of the comparison data and peak-flow means for these watersheds are presented in Table 1. Parameters are defined in Table 2.

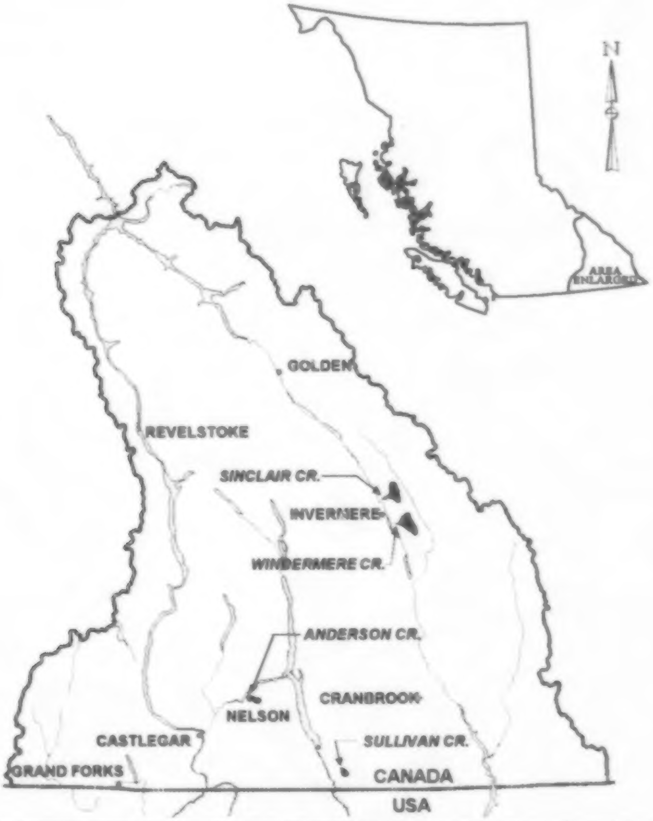

FIGURE 1 *Watershed locations and study area.*

TABLE 1 *Characteristics of selected watershed pairs*

Parameter	Anderson (C*)	Sullivan (T**)	Sinclair (C*)	Windermere (T**)
Peak-flow data pairs	27		19	
Area (ha)	907	622	9430	8420
Harvested area (%)	Nil	17	Nil	32
Gauging stn. elev.	701	975	869	1006
Gauging stn. lat.	49° 30' 12"	49° 06' 14"	50° 37' 45"	50° 29' 03"
Valley flat (ha)	0	0	0	0.5
Lake area (ha)	0	0	0	0
Steep-land area (ha)	0.4	0.2	58	30
Avg. peak flow (m^3/s)	.94	0.35	5.86	1.58
Mean channel gradient (%)	22	24	9	9
Max. basin elev. (m)	6660	7011	8700	8700

* Denotes control.

** Denotes treatment.

TABLE 2 *Definitions of parameters*

Parameter	Definition
Peak-flow data pairs	Maximum number of paired records that could be obtained from existing peak-flow data for selected basin pairs, based on years of concurrent record
Harvested area (%)	Cumulative area harvested for the period of record as a percentage of total watershed area
Area	Drainage area above the watershed gauging station
Gauging stn. elev.	Elevation above sea level of streamflow gauging station
Gauging stn. lat.	Geographic latitude of streamflow gauging station
Valley flat	Total area in watershed adjacent to the drainage network with slopes <7%
Lake area	Total lake area in watershed
Steep-land area	Total area in watershed with slopes >60%
Avg. peak flow (m^3/s)	Mean annual extremes of maximum daily flow over period of study
Mean channel gradient	Gradient of main channel
Max. basin elev.	Maximum ground elevation of watershed

Windermere and Sinclair Creeks

Windermere and Sinclair creeks are situated near each other, on the western side of the Rocky Mountains near Invermere, B.C. Both creeks drain westward and empty into the Columbia River. Most of the Sinclair watershed is located within park boundaries, has not been subjected to past forest development activity, and was, therefore, considered the control in this basin pair.

Sullivan and Anderson Creeks

The Sullivan and Anderson watersheds are much smaller than the Windermere and Sinclair watersheds. Although situated at approximately the same latitude, the Sullivan and Anderson watersheds are located approximately 70 km apart. Anderson was chosen as the control because no harvesting has occurred there.

ASSUMPTIONS

For the purposes of this research, a number of assumptions were required to validate the study methods. Equivalent clearcut area (ECA) was estimated as cumulative area of harvest. Based on a long-term study of the Fool Creek watershed by Troendle and King (1985), it was assumed that the effects of forest harvesting pervade streamflow changes for many years beyond the time of treatment. Thus, recovery effects of revegetation on peak-flow changes were considered negligible over the time period examined. Forest-harvest data for all treatment watersheds included both harvest areas and roads. All data were inclusive of recorded observations up to and including 1993. Environment Canada, the B.C. Ministry of Environment, and the B.C. Ministry of Forests provided streamflow, snow, and forestry data, respectively; and all data were assumed to be correct.

Although it was recognized that other factors, such as aspect, elevation, and location of harvest blocks, and road density, could also affect peak-flow generation, analysis of these relationships was considered beyond the scope of the study.

COMPILATION OF PEAK-FLOW DATA

Peak-flow data were reduced from maximum daily flow to the format required by each analysis technique. Hydrographs of annual freshets were plotted for watershed pairs to obtain the component parts: peak-flow magnitude, time-of-peak, time-to-peak, and peak-flow volume (Figure 2). Peak flow was easily obtained by selecting the maximum annual flow for each target watershed. Time-to-peak and peak-flow volume were obtained by standard hydrograph separation techniques (Dunne and Leopold 1978). Base flow was determined by averaging annual freshet hydrographs for each gauging station and fitting a reasonable line from the average start of the rising limb to the end of the falling limb. Time-of-peak was identified by ordinal date, commencing January 1, and obtained for each freshet hydrograph. Time-to-peak data were the most difficult to extract because criteria used to identify commencement of the rising limb could not be applied consistently to all hydrographs. In some target watersheds, rising limbs were easily distinguished from early-melt effects, but in others the first indication of increased flow was taken to be the start of the rising limb. Peak-flow magnitude and volume were converted to unit measures, based on watershed areas. These components of the hydrograph were required for application of the chi-square test under categorical analysis. Neither time-to-peak nor time-of-peak required similar conversion.

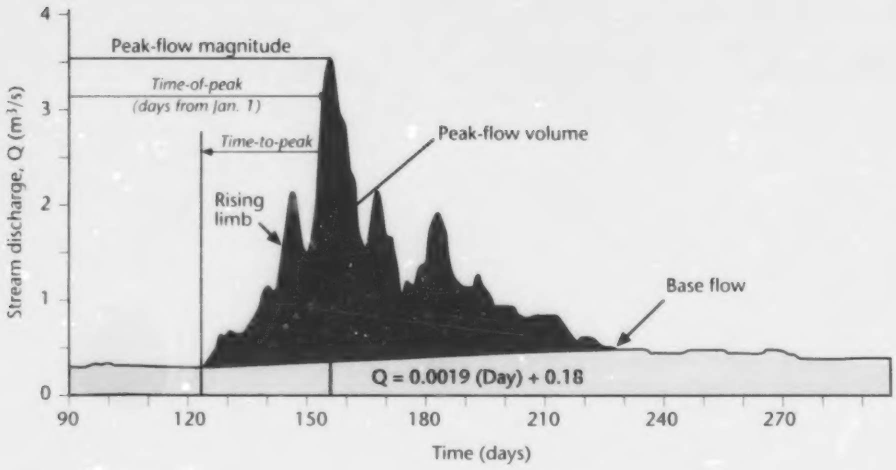

FIGURE 2 *Characteristics of peak flow, Sullivan Creek.*

METHODS

A number of statistical tools were used to analyze data: double-mass curves, cumulative deviations from the mean, maximum likelihood tests, and categorical analysis using chi-square tests. A software program for evaluating statistical power (Borenstein and Cohen 1988) was applied to peak-flow magnitudes, based on chi-square and Student's t-test distributions. Double-mass curves and cumulative deviations from the mean were plotted for visual comparison.

Cumulative deviations from the mean, using peak-flow data from both control and treatment watersheds, were calculated for each basin pair and plotted (Buishand 1982). Sums were rescaled and made dimensionless by dividing each of them by the sample standard deviation. Nonhomogeneous data were indicated when most of the deviations plotted on the positive side of the axis rather than being distributed about the axis. Double-mass curves were fitted to pre-harvest and post-harvest time periods of cumulative peak-flow data for each watershed pair, using regression techniques. Change points were identified using Worsley's statistic (Worsley 1979).

The final phase of this research, categorical analysis, involved a modified station-pairs approach to treatment and control watersheds, wherein differences between treatment and control watershed parameters were sorted into pre- and post-treatment observations for each watershed pair. The approach used in this research differed from that described by Jones and Grant (1996) in that insufficient numbers of paired data were available and this precluded sorting of peak-flow events into several groups. Instead, all sample pairs were considered to constitute a single category for application of chi-square tests. Before analysis, peak-flow magnitude and volume were first converted to unit measures, dividing by watershed area. Indications of change points were demonstrated by Worsley's statistic, as above. Data that fell above and below the pre-treatment average were counted for both pre- and post-treatment periods. These corresponded to the expected and observed categories, respectively, in application of the modified chi-square test.

F2

Graphical plots and statistical tests showed that no single tool was adequate for analyzing changes in peak-flow regime. Results did not support current theory that forest harvesting reduces the time-to-peak and/or increases peak-flow magnitude. Instead, statistics revealed that assumptions about control and treatment watersheds were unjustified. Where control data were expected to be homogeneous over the period of record, statistics indicated that they were heterogeneous. Likewise, where treatment data were expected to be heterogeneous, tests showed that they were homogeneous. In addition, results indicated that increased sample numbers in both watershed pairs were required for 80% statistical power.

Control and Treatment Watersheds

Plotted results of cumulative deviations from the mean showed that while treatment/control designations for Windermere/Sinclair were consistent with data homogeneity (Figure 3), the opposite was true for Sullivan/Anderson (Figure 4). Graphs indicated that peak flow in Anderson (control) had changed during the period of record, although Sullivan (treatment) flows fluctuated about the mean and were, therefore, unchanged.

Results of the double-mass curves showed a remarkable increase in trend slope on the double-mass curve for Sullivan/Anderson, where the change in peak flow coincided with an ECA of 17% (Figure 5). On the other hand, the curve for Windermere/Sinclair did not indicate a significant change in slope (Figure 6), although the change point coincided with an ECA of 22%.

Conventional Statistical Analysis Techniques

Statistical analysis of data involved three test statistics, Q, R, and W (Buishand 1982). All applications of maximum likelihood tests on treatment watersheds failed to reject the null hypothesis (Ho), that peak flow was unchanged, at the 95% significance level (Table 3). However, significance was indicated by two of the three tests for Anderson, the control watershed. This finding was consistent with results of the double-mass curve.

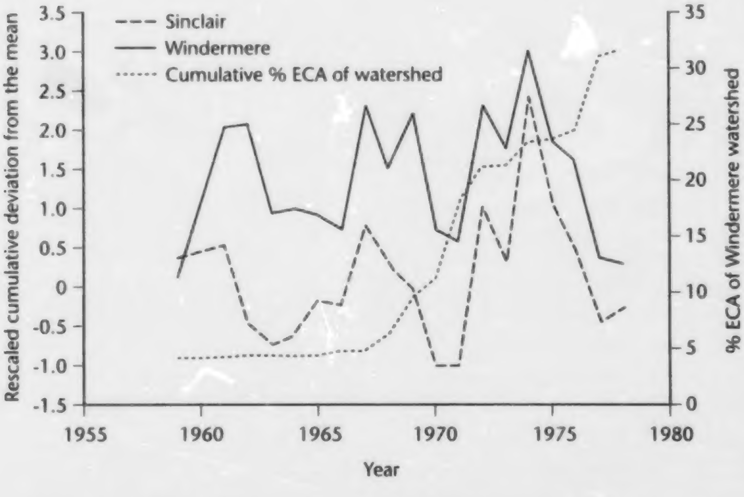

FIGURE 3 *Cumulative deviations from the mean: Windermere/Sinclair peak flow.*

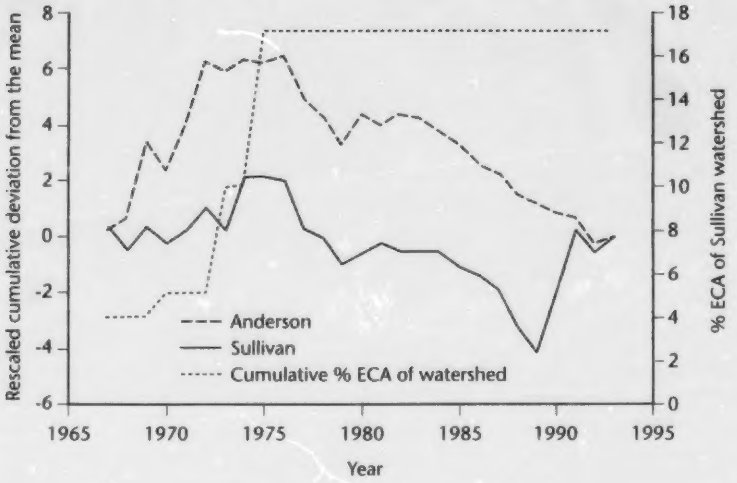

FIGURE 4 *Cumulative deviations from the mean: Sullivan/Anderson peak flow.*

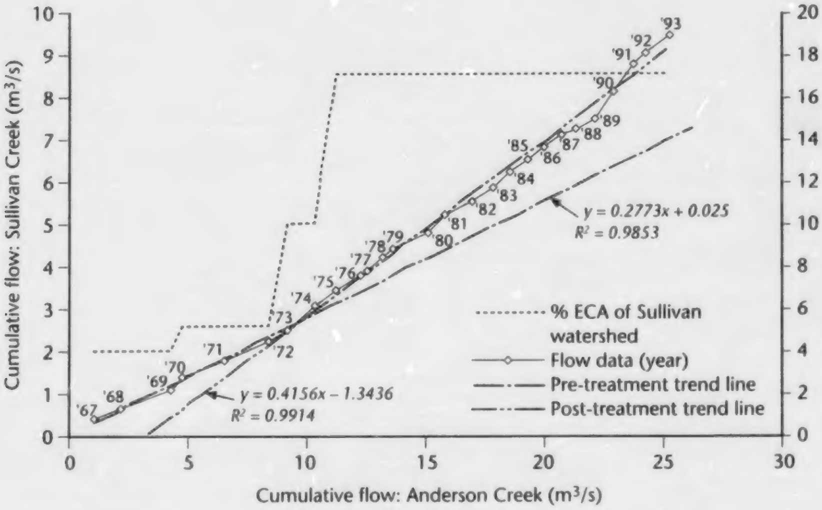

FIGURE 5 *Double-mass curve and* ECA*: Sullivan/Anderson peak flow.*

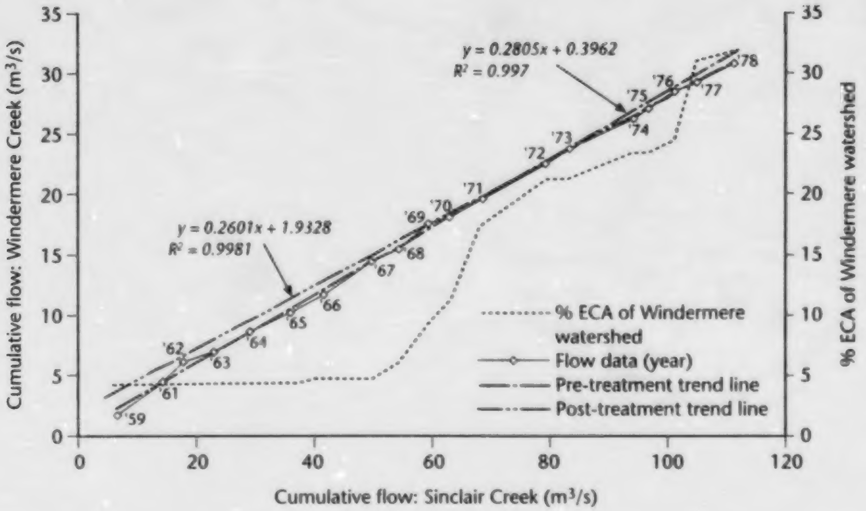

FIGURE 6 *Double-mass curve and* ECA*: Windermere/Sinclair peak flow.*

TABLE 3 *Conventional statistical tests for watershed pairs*

	Maximum likelihood tests		
	Q Statistic	**R Statistic**	**W Statistic**
Windermere	2.71	2.71	0.99
Sinclair	2.84	3.51	0.70
Reject Ho at α = 0.05?	**no**	**no**	**no**
Sullivan	4.12	6.27	0.90
Anderson	**6.46**	6.78	3.46[f]
Reject Ho at α = 0.05?	no	**no**	**no**

f Denotes significance for change after k = 6

Categorical Analysis Techniques

Chi-square tests conducted on peak flow, time-of-peak, time-to-peak, and peak-flow volume agreed with the findings from the analyses above. In the case of Windermere/Sinclair, no change in peak flow was detected, but a significant increase in time-to-peak for Windermere/Sinclair indicated that water contributions to peak flow may have occurred later than they did prior to forest removal (Table 4). For Sullivan/Anderson, with ECA approximately 17%, the results indicated a significant increase in peak flow (Table 4).

Power Analysis

Examination of peak-flow data (Borenstein and Cohen 1988) showed that available data were fewer than that required to ensure dependable results for either of the case studies. Power analysis for Worsley's statistic was based on the Student's t-test option (Table 5). In general, results for the alternative scenario indicated that in excess of 20 pre-treatment and 20 post-treatment samples were required to obtain 80% power and 90% significance for changes in pre-treatment means greater than 30%.

Power analysis of peak-flow data based on the chi-square test revealed that power was low for data analyzed in both case studies (Table 6). As indicated, a large number of samples would be required in the alternative scenario to provide an 80% power of detecting a change, if in fact one occurred.

TABLE 4 *Summary of categorical analysis*

	Categorical analysis - chi-square test: $p(X>\chi^2)$			
	Peak flow	**Time-of-peak**	**Time-to-peak**	**Runoff volume**
Significance level Tested	95%	95%	95%	95%
Windermere/ Sinclair *k = 13* [ff]	0.156	0.892	**0.001**	0.386
Reject Ho at $\alpha = 0.05$?	no	no	**yes**[a]	no
Direction of change in Windermere	increase	increase	**increase**	increase
Sullivan/ Anderson *k = 8* [ff]	**0.001**	0.819	0.678	0.251
Reject Ho at $\alpha = 0.05$?	**yes**[b]	no	no	no
Direction of change in Sullivan	**increase**	increase	decrease	increase

[ff] Determined by W statistic test.

[a] There is a 99.9% chance that time-to-peak has increased in the treated watershed.

[b] There is a 99.9% chance that peak flow has increased in the treated watershed.

TABLE 5 *Comparison of power and sample size for treatment watersheds based on Student's t-test*

	Power analysis of peak flow	
	Available data ($\alpha = 0.05$)	Alternative scenario ($\alpha = 0.10$)
Windermere		
N1[a], N2[b]	13, 7	20, 27
Power	24%	80%
Sullivan		
N1[a], N2[b]	8, 19	18, 28
Power	3%	80%

[a] Corresponds to pre-treatment data.

[b] Corresponds to post-treatment data.

TABLE 6 *Comparison of power and sample size for treatment watersheds based on chi-square test (without Yates correction)*

	Power analysis of peak flow	
	Available data ($\alpha = 0.05$)	Alternative scenario ($\alpha = 0.10$)
Windermere/Sinclair		
N1[a], N2[b]	13, 7	20, 22
Power	**20%**	80%
Sullivan/Anderson		
N1[a], N2[b]	8, 19	20, 22
Power	**40%**	80%

a Corresponds to pre-treatment data.
b Corresponds to post-treatment data.

KEY CONCLUSIONS AND DISCUSSION

The results of a series of statistical tests performed on the two watershed pairs in this study suggested that conclusions of experiments using the paired-watershed approach for detecting changes in peak flow may be unjustified, if some of the assumptions required to apply the method are violated. Furthermore, the results did not support a threshold level of forest harvesting, above which peak-flow changes can be detected.

Consistency of Results with Theory

Neither of the two case studies analyzed behaved as expected. It has been widely accepted that peak flow changes associated with forest harvesting can be detected above 20–25% equivalent clearcut area (ECA). Upon first inspection of treatment effects in the Sullivan Creek watershed (Tables 3 and 4) using the paired-watershed approach, a significant increase in peak flow occurred between 1974 and 1975, corresponding to an equivalent clearcut area of 17%. Although this result was unexpected, further investigation revealed that most of the cause for this change could be attributed to changes in peak flow for the control watershed, Anderson Creek (Table 3), which suggested that a factor other than forest harvesting could have been responsible for the change. A possible explanation for this change might be a shift in the rating curve for the gauging station on Anderson Creek.

Another component of hydrologic response that is thought to be affected by forest removal is time-to-peak. Theory suggests that meltwater may experience shortened lag times because of increased snowpack ablation rates (Hetherington 1987). During the selection process for target watershed pairs, Windermere/Sinclair was considered a good case study for retrospectively applying the paired-watershed approach because cumulative ECA over the period of record exceeded the 20% threshold. Although initial analysis did not indicate a change in peak-flow magnitude, application of chi-square tests to the component hydrograph parts showed that an increase, rather than a decrease, in time-to-peak had occurred. Using this statistic, quantification of the peak-flow change could not be discerned.

Sample Size

An unfortunate constraint of applying the paired-watershed approach to snowmelt-dominated peak flow is that many years of data collection are required to obtain an adequate sample size. One of the greatest obstacles encountered throughout data analysis in this report was the lack of paired data available for candidate watershed pairs. More data would have increased the chance of detecting change. One reason that changes were not detected in this study can be attributed to low statistical power. That is, the failure to reject the null hypothesis does not mean that a change did not occur; it may only mean that sample sizes were not large enough to provide a high statistical power for detecting a change if, in fact, one actually occurred in nature (Peterman 1990).

Results of basin-pairs experiments depend not only on the number of available paired data but also on the extent of potential change from pre- to post-treatment data. In most applications of statistical tests in this study, Ho (no change) failed to be rejected. However, this result did not lead to conclusions that a change in peak flow did not exist. Instead, power analysis showed that, for the range of treatment studied (17–30% ECA) and a 30% change in peak flow magnitudes, years of data in the range of 20 pre- and 20 post-treatment measurements were required to obtain a statistical power of 80%. Commitments for this duration of data collection (40 years plus) are highly unlikely, given shrinking research budgets and changes in corporate or institutional mandates. One alternative to this dilemma would be to set treatment levels sufficiently high so that, likewise, the effect size would be large. Despite adequate considerations for the above parameters, however, assumptions about similarities between control and treatment watersheds may still confound experimental results because background "noise" may override the effects of treatment.

RECOMMENDATIONS FOR EXPERIMENTAL DESIGN

Examining the relationships of changes in peak flow to forest removal is one component of assessing watersheds. In designing paired-watershed experiments, there are a number of factors that researchers should consider both prior to undertaking, and throughout execution of, the study. Typically, a great deal of effort is expended to ensure that basin pairs are similar in geomorphology and climate. Findings from this study suggest that more effort is required to ensure that hydrologic responses are similar. This activity could be undertaken by analyzing long-term hydrologic data in watersheds that are in close proximity. Alternatively, pre-treatment data could be examined using several statistical tools, including those used in this paper.

In general, design of peak-flow, basin-pairs studies should include the following considerations:

1. the areas of control and treatment watersheds should be small (1000 ha or less);
2. the treatment (forest removal) should be executed in a single treatment, and the percentage of treatment by watershed area should be extensive (>30%);
3. the number of pre- and post-treatment data should be large enough to have a high power of detecting change if one exists, say >10 years each; and

4. the assumptions about similar hydrologic behaviour between control and treatment watersheds should be evaluated as collection of pre-treatment data occurs, using statistical tools for testing data homogeneity.

Currently, the *Forest Practices Code of British Columbia Act* requires that cumulative watershed impacts be assessed before forest development plans are approved in Community Watersheds and in watersheds containing high-value fish streams. Potential peak-flow increases are assessed using equivalent clearcut area as a surrogate indicator of peak-flow increases. Given that peak flow has a high degree of natural variability and that our ability to detect changes in peak-flow data is limited, streamflow monitoring intended to measure peak-flow change must be designed to accomplish this objective. Often, the justification for streamflow measurement of forested watersheds is based on determining the effect of forest harvesting. However, without a sufficient calibration period and confirmation of hydrologic similarity between paired basins prior to treatment, there is good chance that potential effects will be unsubstantiated and expected benefits from funding investments unrealized.

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Modelling of Peak Flow Change Using the DHSVM Model

ANDREW WHITAKER, YOUNES ALILA, AND D.A.A. TOEWS

ABSTRACT

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a physically based model that uses a Digital Elevation Model (DEM) to simulate the effect of topography on hydrologic processes. The influence of the forest canopy on the accumulation and melt of snowpack is simulated in an explicit and physically based approach. Model calibration was possible through the use of snow course surveys and snowline air-photo surveys in addition to stream discharge at Redfish Creek experimental watershed near Nelson, B. C., where extensive hourly data are available. The model appears to correctly simulate the influence of forest canopy on the snowpack, and simulated and observed hydrographs are well matched in both calibration and verification periods. Subsequently, 10 harvest scenarios, with varying levels of cutting in different elevation zones, were evaluated over the 5-year period of record (1992–1997). Redfish Creek basin (26 km^2) is divided into four elevation zones based on the hypsometric curve. The three lower zones (700–1880 m) contain operable forest and make up 60% of total basin area, while the high-elevation alpine zone (1880–2300 m) forms 40% of basin area. Results show that harvesting at progressively higher elevations (especially upper forest zone and alpine) causes progressively larger increases in peak flows. There is significant variability from year to year, indicating that the magnitude of peak-flow change depends on the unique weather conditions and seasonal melt pattern in a given year. Cutting in the lowest zone (H80–H100) has little or no effect on peak flow. In the middle forest zone (H60–H80), low-intensity cutting (7% of basin) has little effect, but consistent increases in peak flows are seen with high-intensity cutting (13% of basin). In the upper zone (above H60), low-intensity cutting increased peaks by 6.7–9.5%, while high-intensity cutting produced increases of 13.1–19.4%. A scenario with low-intensity cutting in all forest zones showed a significantly reduced impact on peak flows (except in 1997) even though a greater percentage of basin area (20%) was harvested. Peak-flow change is closely related to harvest elevation(s) and also to seasonal weather patterns in snow-dominated watersheds such as Redfish Creek.

1 INTRODUCTION

Current watershed assessment guidelines in British Columbia assume that peak-flow increases depend on harvest elevation. Here modelling is used to determine changes in peak flows due to realistic harvesting scenarios in various elevation zones in southern interior British Columbia. In particular, the modelling will test current assumptions in the Interior Watershed Assessment Procedure (IWAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) regarding the effects of harvesting on peak flows. One key assumption assigns different weighting to harvesting impacts above and below the H60 elevation on the watershed hypsometric curve. This is a very demanding modelling objective, and one that requires hydrologic processes to be modelled using physical rather than empirical relationships (Abbott et al. 1986). Three important process changes have been determined in considering the effects of forest harvesting; changes in snow accumulation and melt as a result of canopy removal, changes in evapotranspiration during the growing season, and changes in stream channel networks as a result of forest roads and ditches. In considering peak flows, this study is concerned primarily with the first group of processes under snow accumulation and snowmelt, while the influence of forest roads is to be included at a later date. Extensive data from the Redfish Creek experimental watershed are used to calibrate and verify the Distributed Hydrology Soil Vegetation Model (DHSVM) before evaluating forest harvest scenarios. The 5-year data set includes hourly data for several climate stations within the catchment, snow course surveys, and air-photo mapping of snow coverage patterns.

2 DHSVM

The Distributed Hydrology Soil Vegetation Model (DHSVM) is a complex physically based model that uses a Digital Elevation Model (DEM) to simulate the effect of topography on hydrologic processes (Wigmosta et al. 1994) (Figure 1). DHSVM was chosen after a review of six pertinent hydrological models, to assess their suitability in simulating the consequences of timber harvesting on peak flows in British Columbia (Whitaker et al. 1998). The model includes the influence of forest cover and clearcutting on the accumulation and melt of snow, which determines the magnitude of peak flows in interior British Columbia. Data requirements are high and include climate,

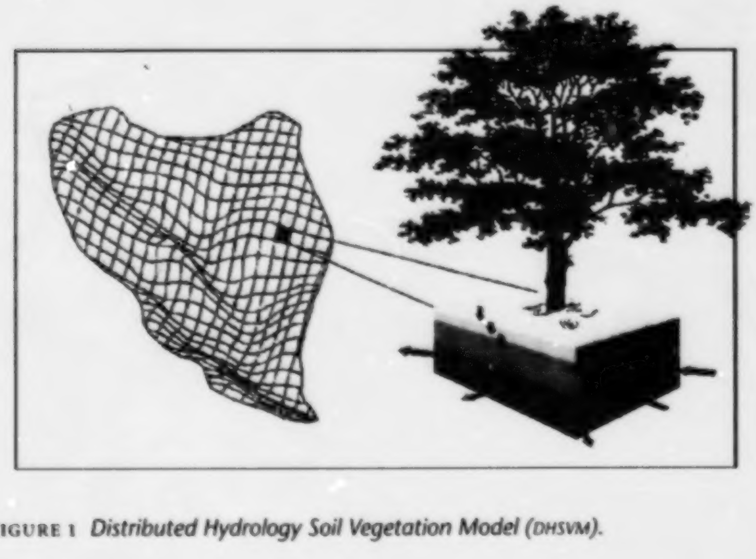

FIGURE 1 *Distributed Hydrology Soil Vegetation Model (DHSVM).*

snow cover, soil and vegetation surveys, and stream flow records. Simulation can be at daily or sub-daily time steps, and so an hourly interval was chosen in this study to allow simulation of the changes to instantaneous peak flows.

DHSVM is distinguished from other hydrologic models in that the spatial distribution of soil moisture, snow cover, evapotranspiration, and runoff production can be simulated at sub-daily time steps (Wigmosta et al. 1994). It consists of a two-layer canopy representation for evapotranspiration, a two-layer energy-balance model for snow accumulation and melt, a multilayer unsaturated soil model, and a saturated subsurface flow model. Climate data input includes precipitation, temperature, wind, humidity, and incoming shortwave and longwave radiation. Digital elevation data are used to model topographic controls on incoming shortwave radiation, precipitation, air temperature, and downslope water movement. Vegetation cover and soil properties are assigned to each digital elevation model (DEM) grid cell or pixel. For each model pixel, the land surface may be composed of overstory vegetation and/or understory vegetation, or just bare soil. As soil and vegetation characteristics are represented explicitly for each pixel across a catchment, it is possible to simulate any number of land-use change scenarios and examine the change in hydrologic response of the catchment.

3 REDFISH CREEK APPLICATION

Considerable time and resources were required in applying DHSVM to Redfish Creek. Information was gathered on the vegetation and forest cover, the soil and terrain characteristics, and multiple climate stations within the study basin. A significant amount of GIS work was involved in preparing soil and vegetation maps, and in analyzing the DEM to derive a stream channel network. A few model parameters could be estimated from standard reference texts, but many required consultation with specialists in soil science, climatology, plant physiology, hydrology, and geomorphology, and with people who have long-term field experience in the study watershed. To assemble all the information, check the quality of 5 years of hourly climate data, estimate missing values, and prepare all of the model input files, represents 9 months of work for a single worker. The model calibration and verification represents a further 3 months of work. Full details on the data preparation, model calibration, and verification may be found in the final reports submitted to the Ministry of Forests (Whitaker and Alila 2000), while this paper focuses on the modelling results and their application in practice.

The Redfish Creek basin (26 km^2) is located on the West Arm Demonstration Forest in the Kootenay Mountains near Nelson, B.C. (Figure 2). The basin has been glaciated, and ranges in elevation from 700 to 2300 m. Slopes are heavily forested, with the lower elevations falling within the Interior Cedar–Hemlock and the upper elevations within the Englemann Spruce–Subalpine Fir biogeoclimatic zones. To date, approximately 10% of the basin area has been harvested. The underlying geology is granitic and is considered to give a relatively tight water balance, so that the majority of the outflow leaves the basin as surface water streamflow.

The completeness of the Redfish Creek data set allows a unique and first-time application of DHSVM in a subalpine forested watershed in interior,

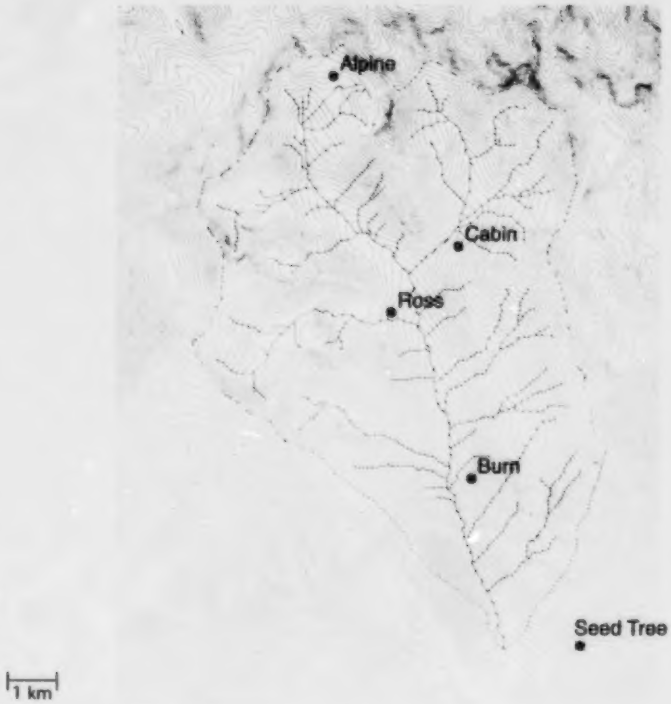

FIGURE 2 *Redfish Creek 25 m contour map derived from DEM and showing gauged basin boundary, derived stream network, and climate stations.*

snow-dominated conditions. At the Redfish Creek experimental basin, extensive hourly data were available for the 5-year period 1992–1997. The important features of the data set are that hourly data are available for both the stream discharge and several climate stations within the watershed (Figure 2). Also of significance is the availability of several snow courses and a snow pillow that allow verification of the snowpack accumulation and melt within the model. Limited data for one tributary stream also allowed the accuracy of internal runoff generation to be evaluated.

The vegetation map and forest cover characteristics for the model were derived from Ministry of Forests operational forest cover maps (FC1 series). Forest stand polygons were grouped together to give 14 vegetation types based on species composition, presence or absence of overstory and understory, vegetation height, stand age, and crown closure (Figure 3, Table 1). Measurements of leaf area index were not available, and the model values were estimated based on species composition and measurements made in the surrounding region.

Soil information was derived from detailed terrain mapping completed for the West Arm Demonstration Forest (Utzig 1997). Several hundred soil polygons were merged to create seven soil classes based on dominant genetic material. Given the absence of detailed field measurements, most soil parameters had to be derived from soil textural class and coarse fragment content that was available for four separate soil layers. Evapotranspiration could remove moisture from only the upper three layers, depending on root depths, and not the lowermost layer.

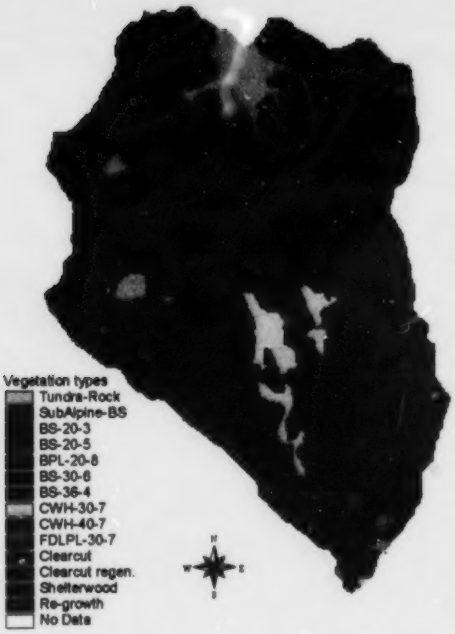

FIGURE 3 *Current vegetation cover for Redfish Creek.*

TABLE 1 *Key characteristics for each of 14 vegetation types*

Veg. type	Description / species	Stand age (years)	Overstory height (m)	Canopy closure (0–1.0)	Leaf area index (LAI)
1	Vegetation absent	N/A	N/A	N/A	N/A
2	Subalpine	200	12	0.2	2.5
3	Balsam-Spruce	180	21	0.3	3.0
4	Balsam-Spruce	140	22	0.5	3.5
5	Balsam-Pine	130	20	0.8	5.0
6	Balsam-Spruce	170	30	0.6	4.5
7	Balsam-Spruce	260	36	0.4	4.0
8	Cedar-Hemlock	160	27	0.65	7.0
9	Cedar-Hemlock	170	39	0.7	7.0
10	Douglas-fir–Larch-Pine	115	29	0.7	6.0
11	Clearcut-no overstory	8	0	0	0
12	Clearcut-early regeneration	10	3	0.1	2.5
13	Clearcut-shelterwood	10	15	0.1	2.5
14	Regenerated clearcut	38	15	0.2	3.0

The gridded DEM required by the model was derived from the 1:20 000 TRIM series or the Province of British Columbia. Gridded DEMs are available for large blocks in the form of NTS 1:250 000 quadrangles that must be subset for the desired watershed. Once within the GIS (ArcView with Spatial Analyst in this application), the DEM is analyzed to define the channel drainage network and delineate the watershed boundary (Figure 2). This is necessary because overland and subsurface flow generation is determined from DEM gradients within the model. An air-photo–derived channel map was used to edit the final channel network. The Redfish Creek DEM contains 41 331 pixels (each 25 by 25 m) with a drainage basin area of 25.83 km^2. For each Strahler channel order, mean values were estimated for width, depth, and Manning's n for channel routing. Final preparation of the channel network and input files requires the use of ArcInfo scripts written specifically for the model.

An hourly time step was chosen to best represent the rapidly changing meteorological conditions during snowmelt events, and the resultant hydrograph response of the basin. To maintain continuity in the model runs, the same two climate stations were utilized for the entire 5-year period: the Burn site, located centrally in the lower half of the watershed at 1220 m; and the Cabin site, located nearer the alpine zone at 1735 m. The key climate variables required are temperature, wind speed, relative humidity, shortwave radiation, longwave radiation, precipitation, precipitation lapse, and temperature lapse.

In conducting a continuous multi-year simulation, particular difficulty was encountered with the winter precipitation record. The accurate measurement of snowfall and rain-and-snow mixtures remains a major difficulty in cold climates. Although the Redfish basin contained a range of storage-type gauges (4-Season, Belfort), their records were too intermittent and unreliable to be of use. A tipping bucket at the low-elevation Burn site proved the most reliable instrument, although an adjustment was necessary to account for under-catch of snowfall during freezing temperatures from November to February. The measured precipitation was adjusted upwards until the simulated snow-water equivalent matched the snow-course data for the Burn and Cabin sites. Snow-pillow data for the higher Alpine site were available for the last 2 years; these data from November to February were used in place of the tipping bucket data, with adjustments for precipitation lapse rates.

4 MODEL CALIBRATION AND VERIFICATION

Calibration and verification of a fully distributed model must include examination of the simulated internal catchment processes, and their patterns and distribution across the landscape. A key advantage of fully distributed models such as DHSVM is that maps can be output for any hydrologic variable for evaluation of the model's performance. Examples include: depth to water table and the extent of soil saturation; subsurface soil moisture flow, snow coverage, and snow water equivalents; and rates of snowmelt. Simulated and observed hydrographs for internal tributaries, as well as for the basin mouth, should be compared in a complete verification of a distributed model. Such complete field data are rarely available, and very few model applications have achieved this level of verification. However, all of the above processes were evaluated in this application of DHSVM to Redfish Creek, allowing a high level of confidence in the final calibrated model and the modelling results.

The processes by which forest cover influences snow accumulation and melt within the model are of critical importance. Snow interception and release processes, and differences in the energy balance of the snowpack due to presence or absence of forest cover, all influence rates of snowmelt and the magnitude of peak flows. The most sensitive parameters are crown closure, leaf area index (LAI), and the radiation attenuation coefficient for the attenuation of shortwave radiation through the forest canopy. While crown closure is a variable that is included in routine forest inventory data, LAI and the radiation attenuation coefficient are more difficult to estimate. This uncertainty in key parameters that influence snowmelt, and potentially peak flows, is a major source of concern. Verification of simulated vegetation influences is made difficult because snow course measurements are usually made only in forest clearings. However, the modelled forest-clearcut snowpack differences look reasonable (Figure 4) and compare well with regional studies where forest and clearcut snowpacks were measured. Additionally, comparison with air-photo–derived snowline maps showed a satisfactory simulation of forest influences throughout the basin. The model closely tracked snowline recession for the available data in 1996 (Figure 5). Comparison of the simulated snowpack and the snow course data showed very good agreement for the Burn and Cabin sites, while some underestimation of snowpack occurred for the other sites (Figure 6).

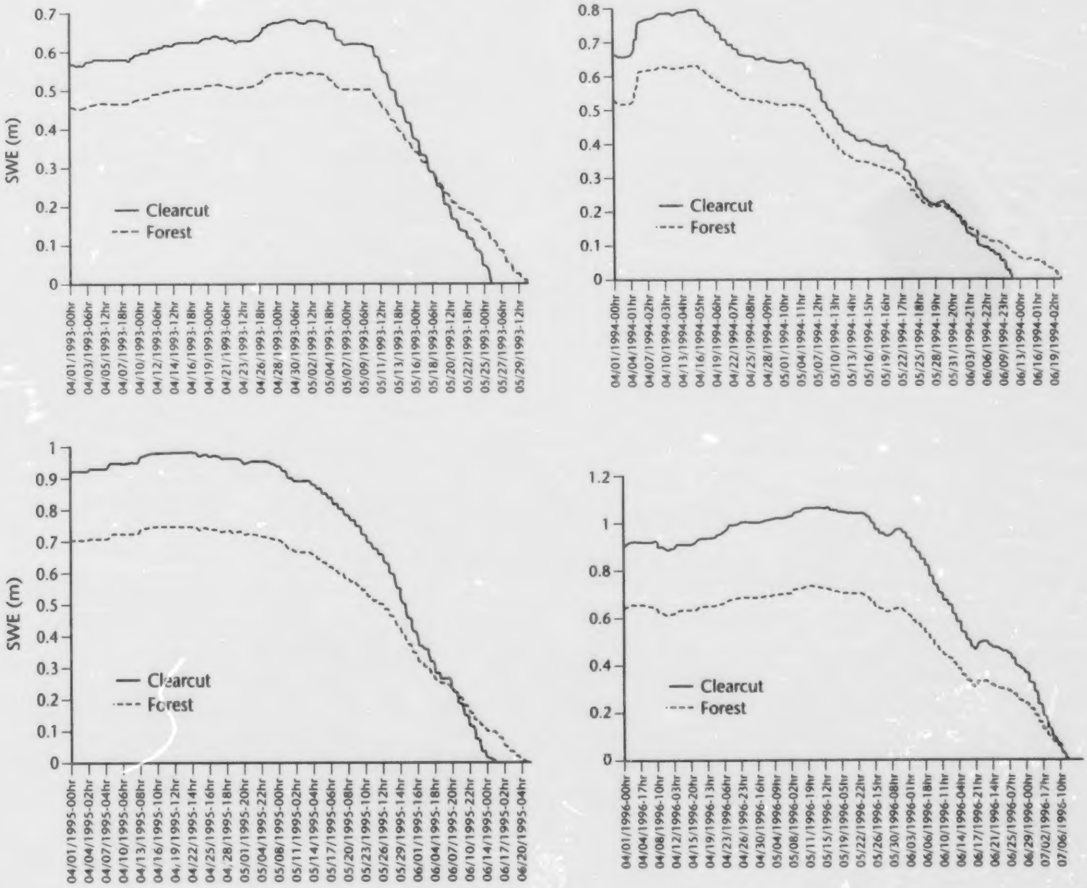

FIGURE 4 *Simulated forest-clearcut differences in snowpack for the Cabin site, 1775 m, 1993–1996.*

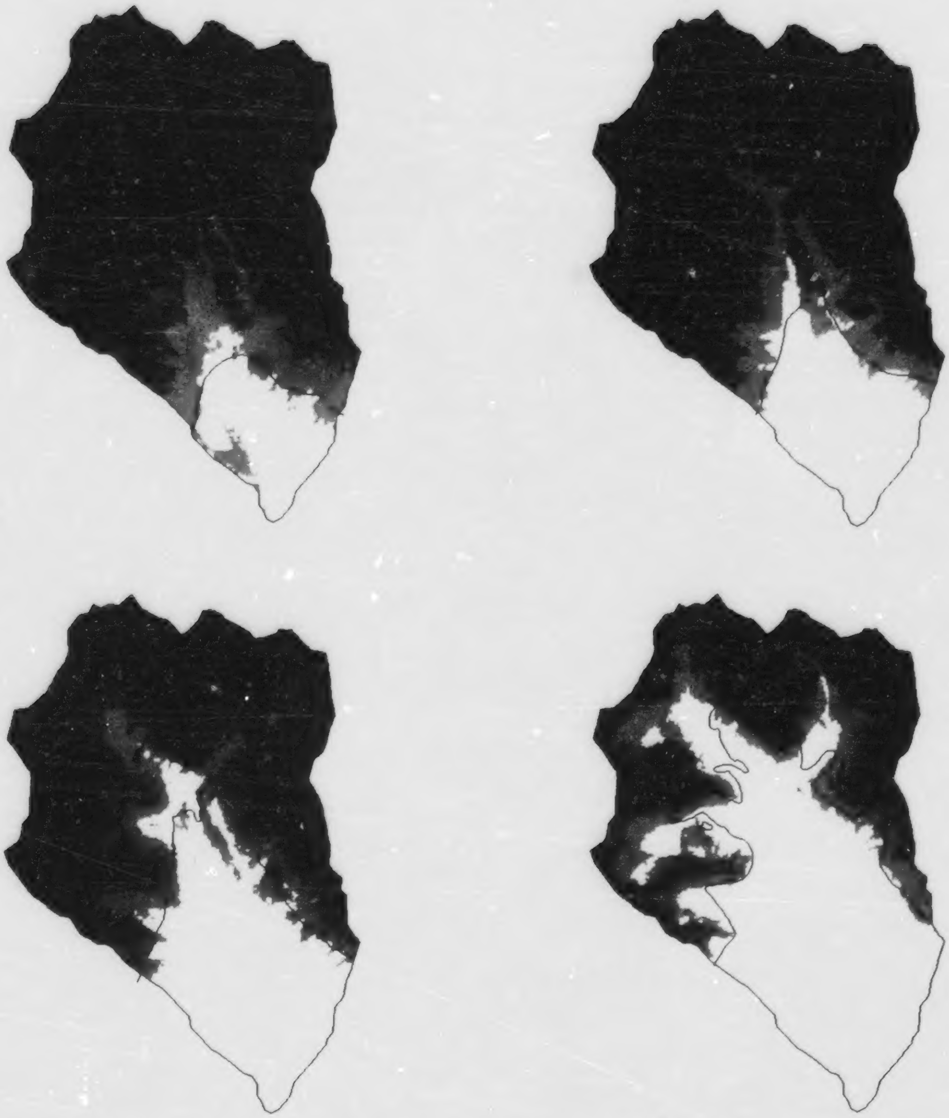

FIGURE 5 *Simulated snow water equivalents for April 14, May 27, June 10, and July 3, 1996, with snowline derived from air-photos for comparison.*

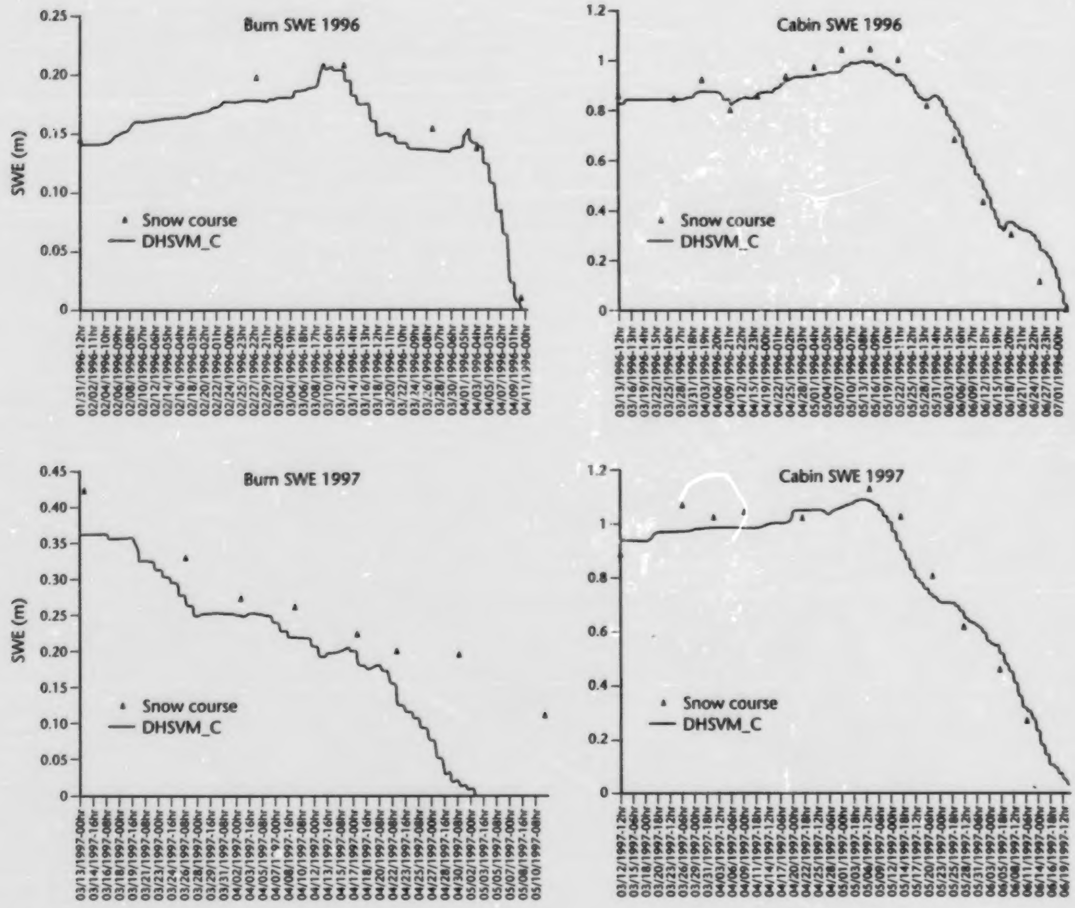

FIGURE 6 *Simulated and observed SWE for 1996–1997 at the Burn (1220 m) and the Cabin (1735 m) sites.*

A critical factor in the ripening and melt of the snowpack is the amount of solar radiation absorbed at the snow surface. This is determined by the snow albedo, which declines over time as the snowpack ages and becomes dirty. The U.S. Army Corps of Engineers (1956) albedo curves were assumed as a starting point, but some adjustment for local conditions is necessary, particularly in basins where radiation snowmelt events dominate spring runoff. Local conditions include contamination of the snow surface by forest litter and dust, shallow snow cover with protruding understory vegetation, and exposed areas of bedrock in steep and rocky terrain. Lowering the albedo curves during calibration was extremely effective in correcting the snowpack simulations and the timing of snowmelt in Redfish Creek.

Permeable forest soils, such as those of Redfish Creek, produce peak flows primarily from rapid subsurface flow and saturated overland flow rather than from infiltration excess runoff (e.g., Woods et al. 1997). Soil conductivity is therefore critical in determining rates of subsurface flow and the extent of saturation and saturated overland flow. In the model, lateral saturated hydraulic conductivity is assumed to be at a maximum at the soil surface, and to decline exponentially with depth. The model was run with a maximum saturated hydraulic conductivity ranging between 2×10^{-4} and 2×10^{-3} m/s, and exponential decay coefficients between 1.0 and 2.0. Parameter values that improved the hydrograph simulation were found to give more realistic maps of the extent of soil saturation. This was taken as confirmation that the model was generating peak flows through the correct mechanisms, and in particular, the correct proportions of surface runoff and subsurface flow. The close match between modelled and observed diurnal flow range, as seen in the hydrographs during snowmelt, is also an indication that the mix of surface and subsurface flow is reasonable.

After calibration, a continuous 5-year model run was completed for October 1992–October 1997. Bearing in mind that the water years 1993–1996 were used in the calibration, while 1997 was held back for verification, the performance of the model can be examined (Figure 7). The degree of fit from one year to the next is relatively constant, despite large differences in the magnitude and nature of the snowmelt runoff over the period of record. Most of the significant peaks are predicted to within 10% of observed flows, with several peaks predicted to within 5% or less. For the final verification year of 1997, the first two peaks are underestimated, while the third is very close. The runoff year with the least accurate simulation is 1994, which contained multiple peaks of approximately the same magnitude over an unusually long period through May and June. Each observed peak is underestimated by about 1.0 m^3/s or 20% in the model, though the pattern of rise and fall is reasonable. Early in the season, in March and April, the model appears too responsive to increasing daily snowmelt, and flows are overestimated in early and late March when the observed flows decrease more rapidly. However, given the complexities of the snowmelt process and the limitations in the climate data for such complex terrain as the Redfish basin, this is a remarkable simulation by the model.

Only after calibration was completed at the basin scale were hydrographs examined for the internal tributary of Upper Redfish. In this way, the comparison of simulated with observed hydrographs serves as an additional verification exercise to test the ability of the model to simulate internal flows and processes. Although the overall simulation is reasonable for all 3 years of record, 1995–1997, the model tends to overestimate the tributary flows and exhibit a more flashy response than observed. This could be attributed to irregularities in hillslope flow pathways, smaller-scale errors in the DEM, soil variability, and the presence of roads in the tributary.

5 ANALYSIS OF HARVEST SCENARIOS

Harvest scenarios were designed according to the delineation of hypsometric elevation zones (Figure 8). The suitability of different parts of the forest for commercial harvest operations depends on such factors as accessibility, forest productivity, regrowth potential, ecological concerns, and visual impacts. Within the Redfish basin, forested areas below approximately 1880 m are generally classed as operable forest, while above this elevation the forest and terrain is typically alpine in character and unsuitable for forest harvest activity. This alpine zone above 1880 m constitutes 40% of the total basin area (above H40 line), and is treated as a single zone in the forest harvest scenarios. Below the H40 line, the operable forest is divided at the H60 and H80 hypsometric elevations of 1740 m and 1520 m to give three additional elevation zones, each representing 20% of total basin area.

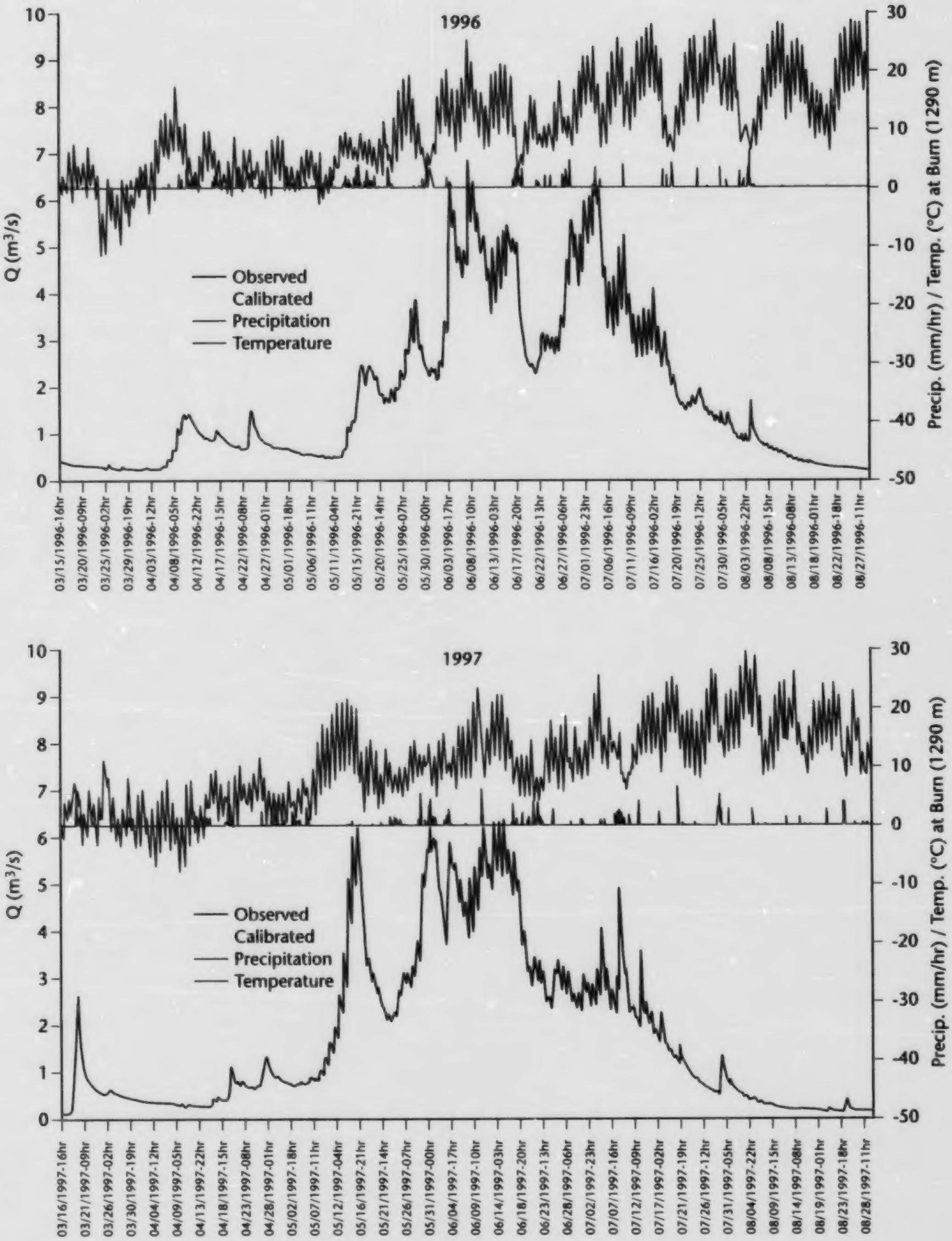

FIGURE 7 *Sample hydrographs for the calibrated model; 1996 calibration period and 1997 verification period.*

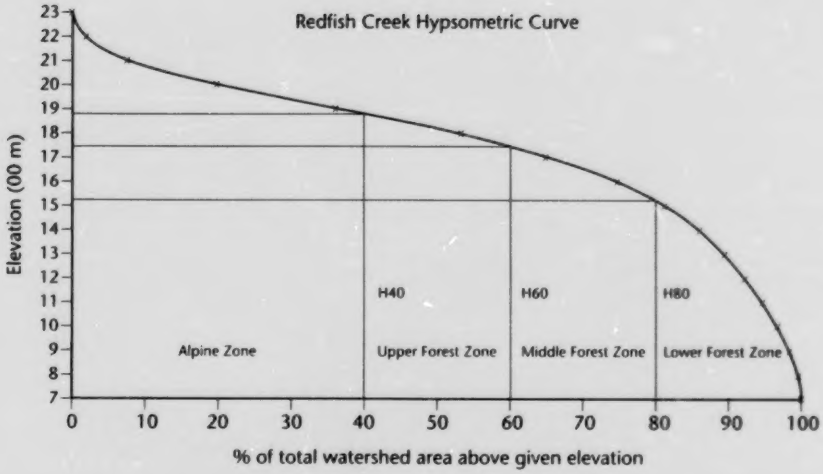

FIGURE 8 *Redfish Creek hypsometric curve.*

Ten forest harvest scenarios were designed to explore increasing levels of harvest across the various hypsometric elevation zones. Previous harvest activity in the watershed has occurred over 10% of the total area, beginning in the late 1960s and continuing on to the current time. There has been significant forest regeneration in the older clearcuts. One benchmark scenario simulated the extreme case of 100% forest canopy removal over the entire watershed, while a second benchmark scenario attempted to recreate a fully mature forest condition, as was present in the early 1960s before logging commenced. Then, for each of the lower, middle, and upper operable forest zones in turn, one-third and two-thirds harvest levels were simulated, representing 6.7 and 13.3% of the total watershed area, respectively (Figure 9). A one-third harvest in the larger alpine zone represents 13.3% of basin area. In contrast, a one-third cumulative forest harvest scenario was simulated across all three operable forest zones to give a total harvest level of 20%. Harvest scenarios were designed by first removing overstory in recovering clearcuts, and then harvesting randomly throughout the older forest stands to make up the desired clearcut area.

The simulated influence of the forest cover on stream flows is first examined for the extreme scenario of clearcutting the entire watershed area. This is compared with the current condition, which has experienced clearcutting over 10% of the basin, and the scenario for fully mature forest cover where pre-harvest conditions are re-created. The clearcut scenario increases the annual peak flow in all 5 years, with peak increases in the range of 40–94%. The largest increases occurred in 1993 and 1997; these are the years in which the hydrograph rose rapidly from the winter baseflow to the annual peak after a cool spring. Late-season peaks were less affected, and flows were reduced during the summer recession as a result of earlier snowmelt. By re-creating the mature forest canopy, peak flows were reduced by 7–11%, but with little change during the summer recession.

A clear pattern emerges for the harvest scenarios in the operable forest zone (700–1880 m). As harvesting moves from the lower to the upper elevations, the impact on peak flows changes from increasing the small, early-season peaks to increasing the late-season peaks. Harvesting in the

FIGURE 9 *Harvest scenarios—red shading shows 2/3 clearcut respectively in lower, mid, and upper operable zones (each 13%), and 1/3 clearcut cumulatively in each of lower, mid, and upper zones (20%).*

lower elevations tends to reduce the magnitude of the annual peak flow because it advances the melt of low-elevation snowpack so that it cannot contribute to the main melt event later in the season. This is commonly referred to as snowmelt de-synchronization, because the timing of snowmelt from different elevation zones is changed so that they are no longer synchronized. The hydrographs also show that the overall timing of the peaks is not really changed by moderate harvest activity. Only the flow magnitudes are affected.

To help in identifying the patterns of peak-flow change across the various scenarios, a 7-day period around the annual peak flow was examined in detail for each of the 5 years. Maximum percent change in the hourly peak flows was extracted in comparing the scenarios with the calibrated watershed condition (Table 2). In addition, the percent change in hourly flows averaged over the same 7-day period was also calculated (Table 3). Excluding the total clearcut scenario, the largest increases in instantaneous hourly peak flows are 19.4 and 19.8% with a 13% clearcut area. When averaged over the 7 days, the peak-flow increases for the same scenarios become 10.6 and 12.3%. These peak-flow changes have the potential to significantly affect sediment transport processes. When considering the impact of peak-flow changes on the stream-channel environment, it is important to consider both the instantaneous peaks and the average flows over several days. Bank erosion and

TABLE 2 *Annual maximum flows from radiation-snow-melt-events—maximum percent change in hourly flows over a 7-day period for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	1993 5/14–5/20	1994 5/7–5/13	1995 5/26–6/1	1996 6/7–6/13	1997 5/15–5/21	Mean
Fully mature forest cover	-11.3	-9.0	-6.9	-11.0	-10.6	-9.8
Total clearcut (100%)	82.3	48.0	39.8	51.0	93.9	63
1/3 cut lower H80–H100 (7%)	-2.8	-1.7	-1.1	-3.5	1.3	-1.6
2/3 cut lower H80–H100 (13%)	-2.4	-1.3	-0.7	-3.3	4.4	-0.7
1/3 cut middle H60–H80 (7%)	1.7	-1.7	-2.0	-2.8	9.2	0.9
2/3 cut middle H60–H80 (13%)	8.8	8.6	5.5	8.0	19.8	10.1
1/3 cut upper H40–H60 (7%)	9.5	7.0	6.9	6.7	8.0	7.6
2/3 cut upper H40–H60 (13%)	19.4	14.2	13.1	13.7	16.7	15.4
1/3 cut alpine H0–H40 (13%)	16.6	10.6	13.4	10.3	13.0	12.8
1/3 cut lower, mid, and upper (20%)	7.6	4.7	5.7	4.3	16.6	7.8

TABLE 3 *Annual maximum flows from radiation-snow-melt-events—percent change in hourly flows, averaged over 7 days, for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	1993 5/14–5/20	1994 5/7–5/13	1995 5/26–6/1	1996 6/7–6/13	1997 5/15–5/21	Mean
Fully mature forest cover	-4.8	-5.7	-4.6	-6.9	-7.1	-5.8
Total clearcut (100%)	43.2	33.7	32.6	33.3	59.2	40
1/3 cut lower H80–H100 (7%)	-0.6	-1.1	-0.5	-1.6	-0.1	-0.8
2/3 cut lower H80–H100 (13%)	-0.4	-0.8	-0.2	-1.5	1.4	-0.3
1/3 cut middle H60–H80 (7%)	-1.1	-1.3	-1.2	-1.5	4.2	-0.2
2/3 cut middle H60–H80 (13%)	2.0	2.2	1.4	2.4	12.3	4.1
1/3 cut upper H40–H60 (7%)	5.8	4.5	5.0	4.5	5.8	5.1
2/3 cut upper H40–H60 (13%)	10.6	9.2	9.4	9.5	11.8	10.1
1/3 cut alpine H0–H40 (13%)	11.2	7.9	9.6	7.8	8.5	9.0
1/3 cut lower, mid, and upper (20%)	4.0	2.2	3.3	1.4	9.9	4.2

entrainment of bed materials may be more dependent on the peak, while overall sediment transport and channel morphology is determined more by high flows over several days or longer. A third analysis looked at changes in the fall-season peak flows that are caused by rainfall and rain-on-snow (Table 4). However, the relatively poor simulation of these fall peaks makes it difficult to draw accurate conclusions from the results of the harvest scenarios. For Redfish Creek, these fall peaks are almost always smaller and less significant than the spring peaks. The following discussion focuses on the instantaneous peak-flow changes (Table 2).

The results show that harvesting above the H60 elevation (upper forest zone, 1740–1880 m) produces a bigger impact on peak flows than does harvesting in the lower elevation zones. Again there is significant variability from year to year, indicating that the magnitude of peak-flow change depends very much on the particular weather conditions and seasonal melt pattern in a given year. Cutting in the lowest zone (H80–H100) has little or no effect on peak flow, and causes a small decrease in peak flows except for the year 1997. Low-intensity cutting (one-third of zone, 7% of basin) in the middle forest zone (H60–H80) has little effect, except for the year 1997 when peaks increased by 9%. Consistent increases in peak flows across all years are seen with high-intensity cutting (two-thirds of zone, 13% of basin) in the middle zone, and in all the harvest scenarios in the upper and alpine zone. In

TABLE 4 *Peak flows from rainfall and rain-on-snow events in the fall—percent change in maximum hourly flow for the scenarios compared to the calibrated model. Calibrated current condition has approximately 10% harvested over past 30 years.*

Scenario	10/26/94	10/10/95	11/29/95	9/17/97	Mean
Fully mature forest cover	-0.8	0.3	3.2	0.8	0.9
Total clearcut (100%)	3.3	-1.6	14	-9	1.7
1/3 cut lower H80–H100 (7%)	0.6	0.9	5.1	0.2	1.7
2/3 cut lower H80–H100 (13%)	1.4	2.1	10	0.3	3.5
1/3 cut middle H60–H80 (7%)	1.1	0.2	3.2	-0.1	1.1
2/3 cut middle H60–H80 (13%)	2.9	0.1	3.0	-0.8	1.3
1/3 cut upper H40–H60 (7%)	0.4	-1.1	-1.5	-1.3	-0.9
2/3 cut upper H40–H60 (13%)	-0.7	-1.9	-2.4	-2.2	-1.8
1/3 cut alpine H0–H40 (13%)	-1.5	-1.3	-1.8	-2.8	-1.9
1/3 cut lower, mid, and upper (20%)	2.1	0	6.9	-1.3	1.9

the upper zone (above H60), low-intensity cutting increased peaks by 6.7–9.5%, while high-intensity cutting produced increases of 13.1–19.4%. Harvesting in the alpine zone had a slightly smaller effect than in the upper forest zone. A scenario with low-intensity cutting in all three forest zones showed significantly smaller impacts on peak flows (except in 1997) even though a greater percentage of basin area (20%) was harvested.

The year-to-year variability in peak-flow increases seems to be related to the pattern of seasonal melt in a given year, and the occurrence of secondary peaks on the rising limb. The greatest peak-flow increases are seen for 1993 (upper and alpine zone cutting) and 1997 (middle zone cutting); these are years in which the hydrograph rose rapidly from base flow to the annual peak without the occurrence of secondary peaks on the rising limb. In other years characterized by rising-limb, secondary peaks, the peak-flow increases were smaller. A cool early spring followed by a sudden warming shows the potential for the greatest peak-flow increases. There is no clear relationship to snowpack volume, with 1993 having the lowest snowpack of the 5 years, and 1997 the greatest.

The model results show that peak-flow change is closely related to harvest elevation in snow-dominated watersheds such as Redfish Creek. Harvesting at higher elevations above approximately 1500 m can cause a significant increase in peak flows of 10–20%, while harvesting at the lower elevations causes little or no change. The same pattern is seen throughout the 5-year simulation period, but there is significant year-to-year variability in the magnitude of peak-flow change. Longer-term simulations would be required to improve quantitative estimates of peak-flow change. Additional snow courses are also required in Redfish Creek to characterize snowpack dynamics beneath the forest canopy. The lack of snow-course data for sites beneath the forest canopy was a major limitation in the verification of simulated canopy influences in this study. However, the model is shown to simulate the snowpack in the openings and the snowline retreat on forested slopes very closely.

Harvesting in the upper elevations has a significantly greater impact on the annual peak flows than harvesting at lower elevations. Harvesting in the lowest elevation (H80–H100) zone had no impact of peak flow. Harvesting in the next highest (H60–H80) zone had a minimal effect at 7%, but a considerable effect at 13%. Harvesting effects are considerable in the H40–H60 zone in all years, and the increase is proportional to the amount harvested. The percent increase is considerably greater in this zone than in the zone below. This more consistent increase in peak flow in this zone with timber harvested, and the greater increase as a ratio of percentage harvested, would lend justification to weighting harvesting above the H60 line more than below. The results of Gluns (2001), where he follows the snow-retreat line during peak flow, also adds some justification to the H60 line, because the snow tends to be disappearing at this elevation when the peak occurred. However, in some years with an early peak, there is still considerable snow left below the H60 elevation.

There has been some question as to the applicability of the H60 concept to throughout the interior of British Columbia. The model results are likely applicable to watersheds with a similar hypsometric curve and a substantial alpine area. In an area with a flat hypsometric curve, there would likely be less differentiation between elevation zones because accumulation and melt would not increase as much with altitude. In a watershed without an alpine area, the harvesting effects would likely be greater because all elevations, including the highest elevations, would be subject to harvesting. It would be useful to continue this type of modelling work to consider the alpine effect, the effects of roads, the longer-term effects of harvesting, and the effects of harvesting in watersheds with differing hypsometric curves.

The importance of individual watershed topographic characteristics must be stressed in determining snowmelt and peak-flow generation. Examination of the hypsometric curve may reveal a high proportion of total basin area within a narrow elevation range; for example, where there is plateau terrain. Peak flows will be particularly sensitive to harvesting in these areas of gentle slopes, because snowmelt is simultaneous across the entire zone. There is a danger that such individual watershed characteristics will be overlooked if an across-the-board threshold elevation is adopted in management guidelines.

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Stream Channel Assessment in the Interior of British Columbia

DAN HOGAN

ABSTRACT

The Channel Assessment Procedure referred to in the Watershed Assessment Procedure was developed to provide an objective, repeatable method to assess stream-channel disturbance. It is based on field indicators of disturbance that were developed with an understanding of the naturally high variability of stream channels. The indicators relate to channel aggradation and degradation that can be linked to the primary hydrologic and geomorphic processes operating in a watershed. The channel assessment of Norns Creek is described to provide an illustration of the utility of channel assessment as a component analysis within a watershed assessment. The channel assessment provides a detailed description of the channel reaches, including morphology, hillslope/channel coupling, and sediment transport and deposition sites. With the accompanying geo-referenced inventory of disturbance indicators, the experienced geomorphologist can then link watershed processes and channel conditions. This information is relevant to fish habitats and can form the basis for determining appropriate watershed restoration prescriptions.

INTRODUCTION

Watershed assessment involves consideration of several hydrologic and geomorphic processes, as discussed previously (Chatwin 2001). An underlying assumption of the Watershed Assessment Procedure (WAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1996a) is that changes in these physical processes may lead to changes in downstream channels; that is, the channel integrates all of the upslope/upstream disturbances. Therefore, one of the WAP process components involves assessing the physical condition of stream channels in the watershed. The goal of this presentation is to review the Forest Practices Code field guide entitled the "Channel Assessment Procedure" (CAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1996b) and to consider its suitability for use in interior areas of British Columbia. The CAP outputs that are relevant to the practicing forester or hydrologist will also be considered.

This presentation will cover three themes. First, the CAP will be briefly outlined to provide a basis for helping the forester or hydrologist to understand what can be expected from the procedure. Second, the basis for the assumption that channels integrate watershed processes will be explored. Finally, an interior example will be presented to illustrate what watershed-relevant information is available at the conclusion of a CAP.

CAP BACKGROUND

A method to evaluate channel disturbance was required as a component of the WAP. Channel disturbance refers to changes to the stream bed and/or bank characteristics, such as excessive bank erosion or in-filling of the channel with sediment. Although several stream-channel *classification* systems existed, there was no readily applicable technique to determine disturbance. That is, there were few or no channel *assessment* capabilities in the existing classification systems. Also, there were problems applying existing classifications to the WAP. For instance, in small streams that are not visible on conventional aerial photographs (streams with bankfull widths less than approximately 20 m) there was usually no way to determine what the channel would have been classified as before logging. Therefore, without the use of aerial photographs, there is no pre-disturbance channel information. In these cases there is no way to assess either the extent or cause of channel change. Additional problems arise when applying other existing classification schemes to our local environments because of differences in hydrological and geological factors (Ashmore 1999).

The CAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1996a and b) was developed following guidelines suggested for evaluating channels by Kellerhals et al. (1976). They recommended that the drainage system be divided into reaches with homogeneous morphologies and valley flat/channel relations. Further, they argued that the system should be consistent with the succession of channel types found within a watershed. Finally, they recommended that standard terminology be used to ensure consistent results. These guidelines were incorporated during the development of the CAP. Based on our review of many different types of stream surveys, several other points were considered important in the development of an assessment method. The points underlying the final CAP are:

1. the need to avoid problems associated with streamflow, stage-dependent measures;
2. the need to avoid use of highly intensive, repetitive, and non-reproducible field measures;
3. an awareness and understanding that undisturbed channels are highly variable; and
4. an assessment of channel disturbance that must account for the fact that channels naturally exhibit cycles of aggradation and degradation.

Points 1 and 2 above reflect the desire to develop an objective, repeatable method to assess stream-channel disturbance. For example, considering Figure 1, it is evident that as streamflow increases the spatial extent of pools and riffles changes in a non-proportional manner. In Figure 1a the water surface is dominated by low-velocity streamflows typical of pools at low discharge. As the discharge increases (Figure 1b) there is shift towards more fast-flowing, riffle environments. In flood, the channel consists of one continuous riffle

(a)

(b)

FIGURE 1 *Changes in pool and riffle extent with increases in streamflow at Carnation Creek on Vancouver Island. Figure 1a is low flow (Q<1 m³/s), 1b is moderate flow (Q≅3 m³/s), and 1c is high flow (Q≅30 m³/s). Figure 1d shows the faster rate of increase in flow velocity in pools with increasing discharge compared to riffles (from Hogan 1986).*

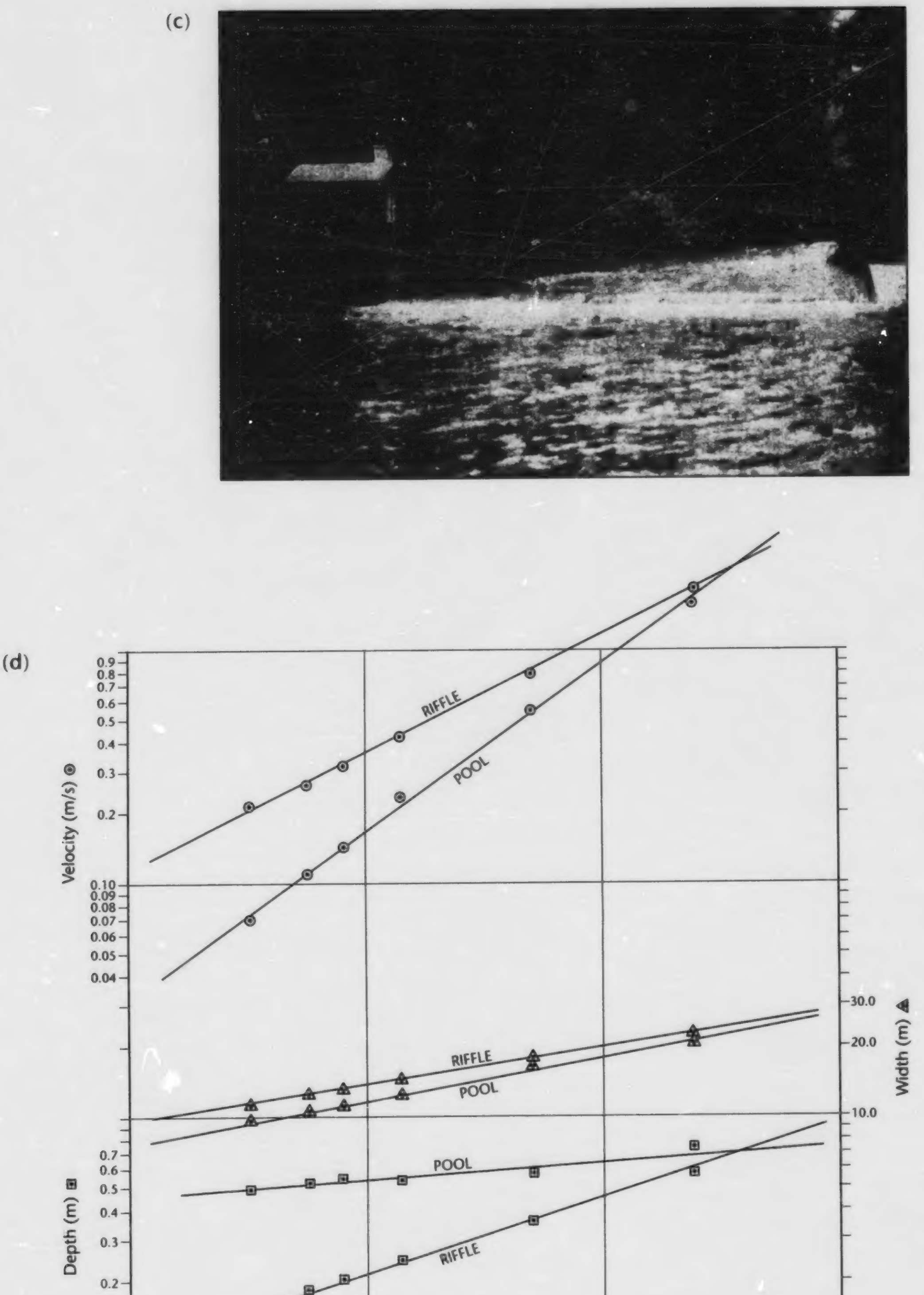


FIGURE 1 *Continued*

(Figure 1c) and no pools are present. The relatively rapid increase in streamflow velocities with rising discharges measured in pools compared to riffles is evident in Figure 1d. It is difficult to see how it is possible for repeatable measurements to be made of pool and riffle characteristics (width, surface area, volume, etc.).

The important influence of large woody debris (LWD) on stream-channel morphology and fish habitats has been recognized for over two decades. However, very little attention seems to have been paid to the difficulties encountered when attempting to accurately measure a single piece of LWD, let alone the many pieces found on log jams. A review of annual field records from the "physical stream study" at Carnation Creek on Vancouver Island shows several problems (details about the Carnation Creek study can be found in Hogan et al. 1998c). The LWD volumes included in Table 1 were calculated from measurements made by trained, but different, surveyors each year from 1971 to 1988. Only those logs that could be positively identified each year are considered.

The volumes measured for the same log over time by different people can be dramatically different (Table 1), with extreme examples of logs being out by a 15-fold difference. This highlights the difficulties in obtaining repeatable measures of what appear to relatively simple objects (e.g., logs do not hide or try to avoid measurement like fish will). The possible reasons why the values in Table 1 are so different may be because:

- difficulties and inconsistencies are encountered when trying to measure root-wads;
- logs are rarely perfectly cylindrical, so measurement of log diameter varies;
- since the log volume is calculated by $\pi(d/2)^2l$, where d is log diameter and l is log length, the calculation is very sensitive to errors in the measurement of d; and
- the log length can be inconsistently measured, depending on how the overbank portions of the log are included.

The measurement difficulties increase exponentially when dealing with large accumulations of logs, or LWD jams, Although no qualitative examples are available, the measurement problems are obvious in the photographs of LWD jams shown in Figure 2. Measurement of every individual piece is impossible; there are many buried logs in Figure 2a that cannot be measured,

TABLE 1 *LWD volumes calculated from annual field surveys at Carnation Creek between 1971 and 1988. Measurements were made by trained, but different, surveyors each year. Only logs that could be positively identified each year are included.*

LWD number	Max. volume (m^3)	Min. volume (m^3)	No. of years	Difference
1	98.11	24.21	18	3.7 X
2	69.58	28.07	18	2.5 X
3	19.44	16.87	18	1.2 X
4	35.37	11.94	18	3.0 X
5	20.13	1.29	18	15.6 X
6	23.14	2.70	18	8.6 X
7	15.71	2.45	18	6.4 X

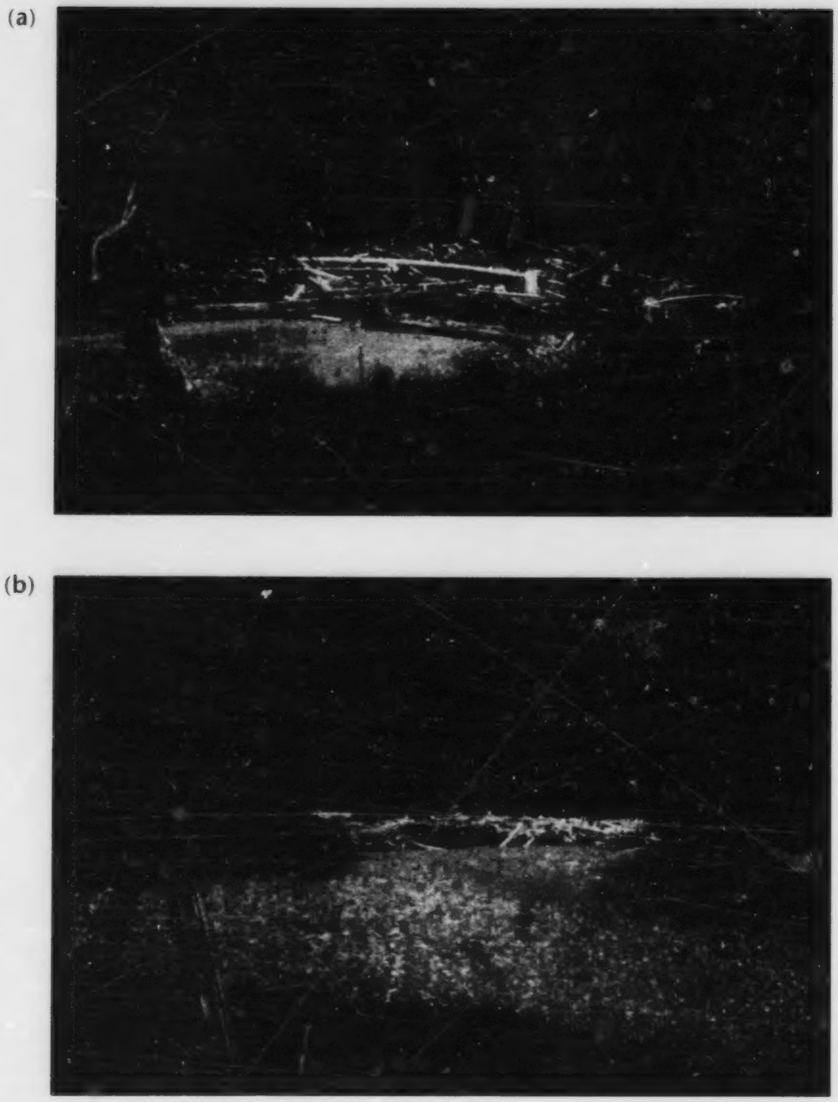


FIGURE 2 *Examples of LWD jams in streams to illustrate the difficulties inherent in measuring debris. Figure 2a is an LWD jam in Carnation Creek. Figures 2b and 2c are in streams in the Queen Charlotte Islands. The jam in Schomar Creek (Figure 2b) is composed of many small pieces of debris. The debris pile in Shelly Creek (Figure 2c) was formed by blown-down trees as a result of an extreme wind storm.*

(c)

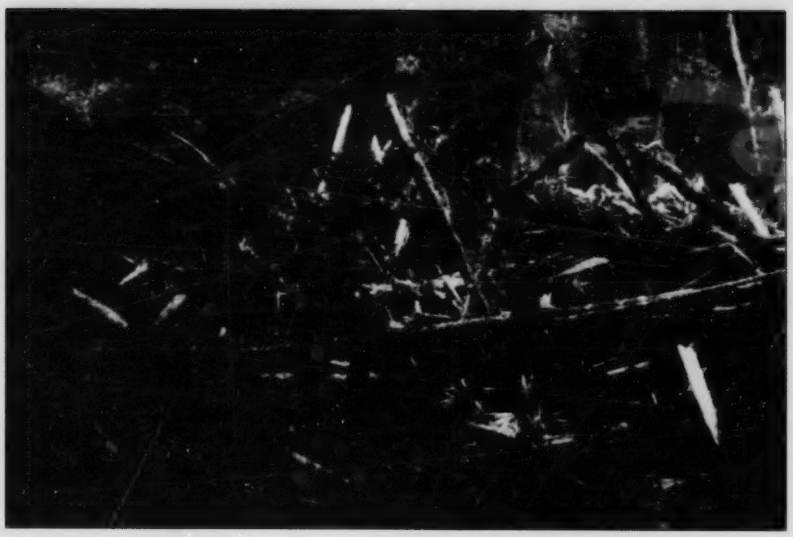


FIGURE 2 *Continued*

many pieces that may not even be defined as "large" in the LWD context (>0.3 m diameter and >3.0 m long) in Figure 2b, and the simply overwhelming number of trees, stems, branches, and roots in Figure 2c. LWD jams are not rare features in coastal, forested, watershed streams (Hogan et. al. 1998b,) and preliminary results from interior streams indicate that jams are also prevalent in all other areas of the province (Hogan and Bird, on-going FRBC project).

Several other examples of stage-dependent and non-repeatable field measures can be cited. The examples considered here simply highlight a problem that is often ignored outright or glossed over as irrelevant by stream surveyors. The CAP intentionally tried to avoid these problems.

Another consideration underlying the development of the CAP involves an awareness of the highly complex and diverse nature of stream channels in forested watersheds. As a result, the natural variability of channel conditions is considered explicitly in the CAP. There are cycles of degradation and aggradation and these cycles are initiated by various types of natural disturbances. In one example, Schwab (1998) has documented the historical rate of landslide events occurring over the last 200 years on the Queen Charlotte Islands. He shows that over 85% of all sediment and debris derived from hillslope areas and delivered to the stream channels by landslides occurred during four major storm events (1891, 1917, 1935, and 1978). These episodic landslide events initiate the channel changes that persisted for over half a century (Hogan et al. 1998a). For example, a typical deposition/erosion cycle is shown in Figure 3. This illustrates the progression of changes that occur along a channel reach as the result of the formation of an in-stream large debris jam. In this case, the channel disturbance was initiated by a landslide that delivered large volumes of sediment and debris to the channel, but similar channel processes occur in areas subject to large floods, wildfires, and insect infestations, all of which generate abnormally large, episodic inputs of sediment and debris to the stream system.

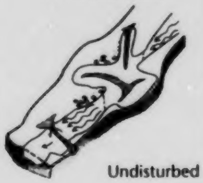
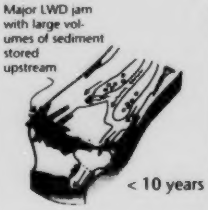
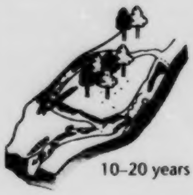
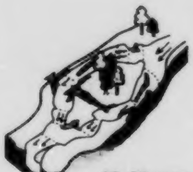
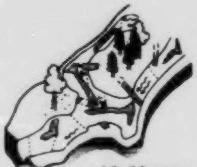
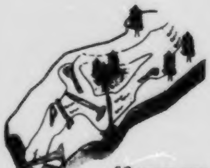
Downstream		Log Jam Evolution	Upstream	
Channel Characteristics	**Effects on fish habitat**	**Time since disturbance**	**Effects on fish habitat**	**Channel Characteristics**
• same as upstream	• productivity, capacity for salmonid spawning and rearing in most stable condition, diversity of pool and riffle types meet habitat requirements at life stages, several species.	 **Undisturbed**	• same as downsteam	• diverse morphology: high width, depth, and sediment texture variability, pool length = riffle length, diagonal riffles, lateral scour pools • LWD primarily diagonal to streamflow, many small debris steps, infrequent larger debris accumulations (jams), abundant undercut banks, LWD functions at all flow levels
• single straight channel • coarse-textured bed • riffles, (slip-face & cascade), few pools • LWD parallel to channel •mainly over-hung banks rather than undercut •few LWD steps (i.e. few small sediment storage sites associated with LWD)	• quantitity of salmonid spawning sites reduced, or non-existent on bedrock • poor survival in redds scour of limited gravel • access for adults and juveniles difficult, or lost at low flows • cover in pools in jam reduced and less stable elsewhere	 Major LWD jam with large volumes of sediment stored upstream **< 10 years**	• more spawning area,but lower survival of eggs and fry • rearing habitat reduced for pool-dwelling species (i.e. coho) • riffle habitat reduced for species in boulder and LWD cover (i.e. chinook fry, steelhead parr) • dewatered sites & intergravel flow limit fish usability • increase in off-channel overwinter sites, but unstable, seasonally accessible and possible isolation at low flow •migration barriers or increased predation during adult, smolt and fry migrations in shallow habitats that lack cover	• braided channel • minimal undercut banks • fine texture surface layer of bed
• few channels, increased sinuosity due to debris and stone lines • bar development mainly mid-channel, few diagonal • bed sediment finer as sediment moves down over jam • pools associated with debris • channel usually straight riffle between lateral scour pools pieces (LWD parallel and wads)	• increasing productive spawning and rearing habitat, in larger number but smaller size of riffles and pools • unstable cover, mobile LWD, but improved rearing sites in small pools • increased bedload movement, depth of scour decreases survival for eggs and fry • access may remain difficult •deep pool habitat with cover reduced for older age classes of rearing species, spawning adults, and over-winter juveniles	 **10–20 years**	•towards more usable sites with cover for salmonid rearing • higher survival in redds as fines removed, flows through gravel improve • fewer or cut-off side channels, less over-wintering sites, which are more stable	• reduced number of main channels, increased sinuosity due to debris • fine sediment removal leading to coarser bed • pools associated with debris (LWD parallel and wads) • channel gradient steeper overall
• one or two main channels • bed sediment finer • pools more extensive • riffles less extensive • channel gradient less steep overall	• same as upstream	 **20–30 years**	•habitat improves for salmonid spawning and rearing • habitat becoming more stable • multiple channels decrease the magnitude of individual spawning and rearing sites, but there are more of them	• one or two main channels • bed sediment coarser * pools more extensive • riffles less extensive • channel gradient steeper overall
• downcutting continues • stable diagonal riffles • pools and riffles extent approximately square • pool type more diverse (plunge, lateral scour, dammed, back water, etc. (see Bisson 1982)	• same as upstream	 **30–50 years**	• habitats are becoming more accessible, more productive, and usable habitat for spawning and rearing is diversified and increasingly stable	• same as downstream
• previously buried debris uncovered and begins to function (i.e. effectively traps sediment and produces scour holes and pools) leading to more diverse channel conditions	• same as upstream	 **< 50 years ago**	• recovery to nearly undisturbed condition assuming there is an adequate supply of stable LWD	• side channels • complex channel • same as "never" above

FIGURE 3 *An example of a typical cycle of degradation and aggradation (Hogan et al. 1998).*

Debris jams, such as shown in Figure 3, interrupt sediment transport down the reach. This leads to the development of a large sediment wedge on the upstream side of the jam. In the vicinity of this aggradational wedge, the channel undergoes major changes. The banks erode in response to increased bar development, the channel changes from a single thread to multiple branches or braids, sediment textures are finer, pools are in-filled, and LWD is buried. In contrast, downstream of the LWD jam, the channel is scoured away because sediment removed during floods cannot be replenished from upstream due to the jam forming a barrier to sediment transport. In this degradational zone, the bed erodes, thereby removing LWD pieces, causing coarser sediment textures, loss of pool areas, and more extensive riffles and runs. Over time, the channel returns to pre-disturbance conditions as the jam deteriorates and sediment and debris previously stored upstream are released and transported downstream. The morphological adjustments to the breakdown of the jam are shown in Figure 3.

The longitudinal profile of a section in Tango Creek, located east of Radium Hot Springs, is drawn in Figure 4. Tango Creek is a small interior stream with a bankfull width of just under 5 m, with a stream gradient of 9% and a boulder/cobble bed. The longitudinal profile shows the typical step-pool sequences, but it also shows a large sediment wedge in the upper section (near 180 m). This wedge has developed behind a LWD jam, and the channel characteristics associated with it are identical to those described for the coastal example. On-going studies (FRBC) show that this type of channel behaviour is normal in all areas of the province.

The examples presented here are from old-growth, unlogged, forested watersheds. The challenge in developing the CAP was to incorporate these complex measurement and watershed process aspects into a systematic assessment procedure. The CAP attempts to accomplish this objective. This is an important point because the intention of the WAP is to determine the impact of resource management on the health of a watershed and its

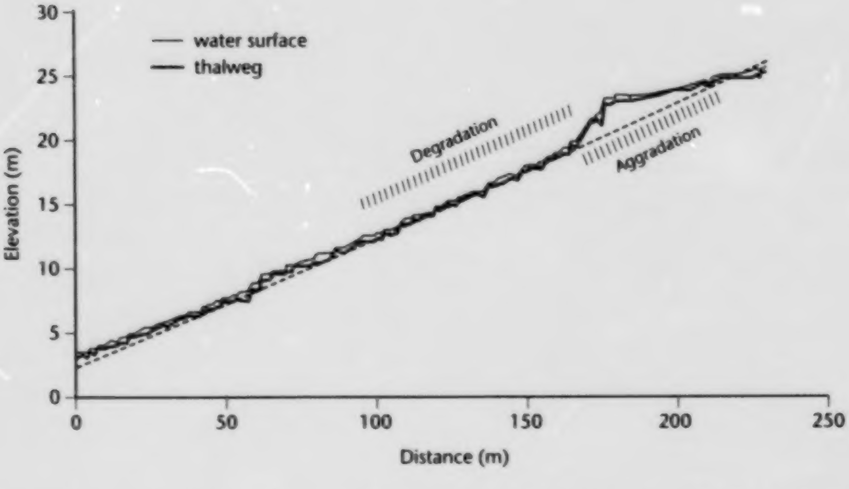


FIGURE 4 *Longitudinal profile from Tango Creek, a small watershed east of Radium Hot Springs. A step-pool morphology is shown downstream of a large sediment wedge that causes an aggradation/degradation cycle within the channel. The dashed line is a second-order polynomial regression line for visual comparison with the longitudinal profile.*

stream-channel network. In order to attribute channel conditions to a human-induced cause, the natural variability must be taken into account. The CAP identifies disturbance attributes, but it is up to the hydrologist's experience in fluvial processes to distinguish between natural and human-induced channel changes.

STREAM CHANNELS AND THE CAP IN A WATERSHED CONTEXT

Many of the physical factors that control stream-channel environments are a function of processes operating at the watershed scale. That is, the channel morphology at any point along the drainage network is strongly influenced by physical processes operating in upstream catchment areas, since stream channels transfer water, sediment, and debris from headwater areas downstream along the drainage network to the stream mouth. The physical shape of each channel along the network results from the interaction of sediment and debris being transferred and stored through the drainage system.

The nature, severity, and duration of stream-channel disturbances are also partially dependent upon watershed considerations. Headwater streams are often more resilient to disturbance, and recover more quickly, than larger downstream channels. Headwater channels are commonly coupled to the hillslope, so the fluvial environment is directly influenced by terrestrial processes. Conversely, streams located further downstream have relatively lower channel gradients, finer-textured bed sediments, and alluvial banks. These channels, although not coupled to the hillslope, are prone to fluvial disturbances resulting from relatively small storms; often the damage can persist for decades

The general physical characteristics of a stream, including its channel shape and appearance, depend on many watershed factors. Those that govern channel conditions have been summarized by Church (1992):

- flood regime characteristics of the stream,
- amount, timing, and nature of sediment delivered to the stream,
- nature of the materials through which the stream flows, and
- local geological history of the area.

Several secondary factors also govern channel appearance:

- local climate,
- the nature of riparian vegetation,
- human modification of the channel (direct effects), and
- land use (indirect effects).

These factors interact to produce a wide array of different channel types, each with varying bank, bed, bar, and planform pattern characteristics (Figure 5). The variety of possible channel types is a function of the dynamics of channel stability and sediment supply.

Although the specific characteristics of a stream depend on many factors, certain generalities are evident at the watershed level. Flood regime, sediment delivery, and material types vary along the drainage network. In a typical watershed, channel morphology changes with distance from the drainage basin

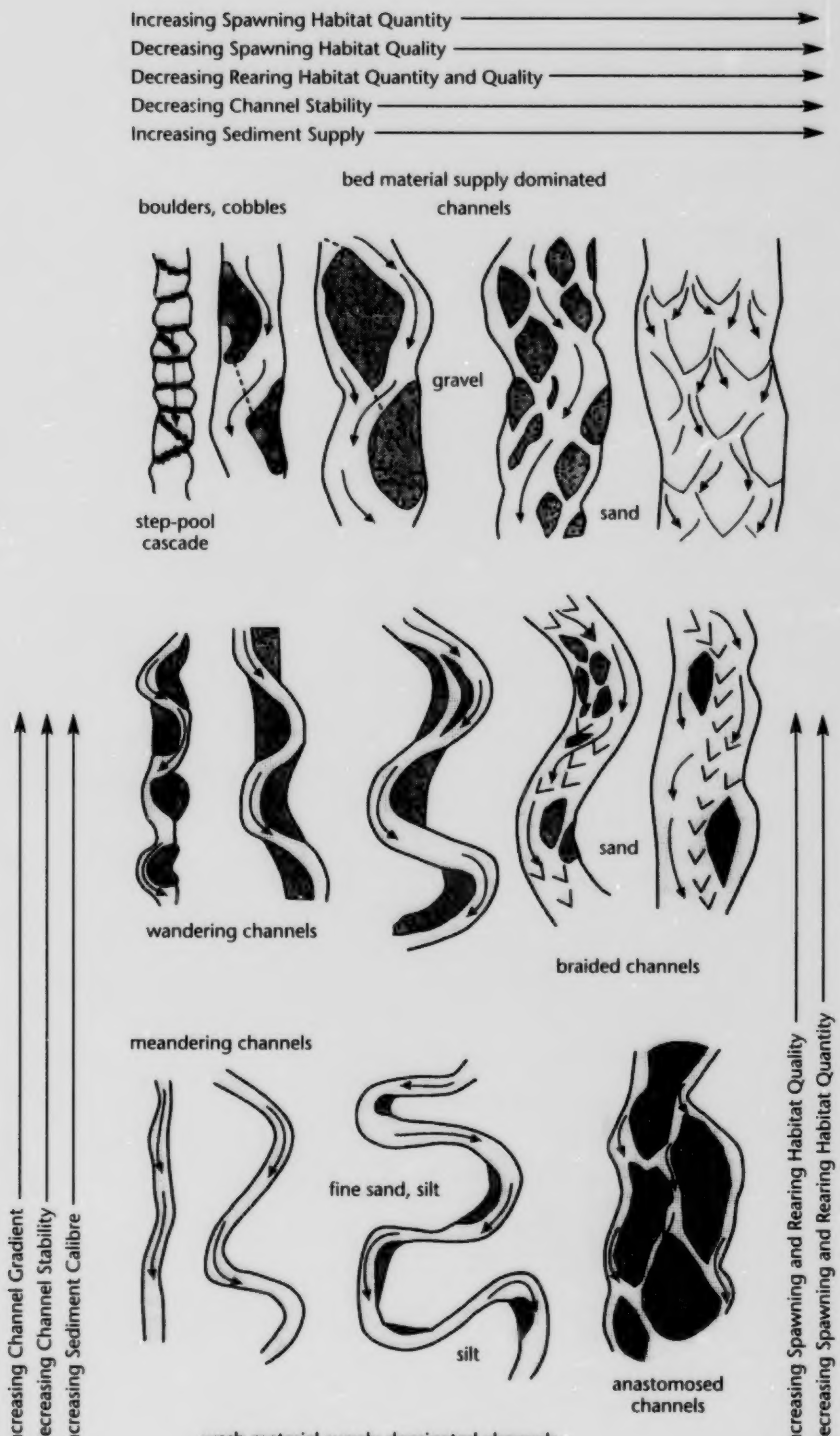

Increasing Spawning Habitat Quantity
Decreasing Spawning Habitat Quality
Decreasing Rearing Habitat Quantity and Quality
Decreasing Channel Stability
Increasing Sediment Supply
bed material supply dominated channels
boulders, cobbles
gravel
sand
step-pool cascade
wandering channels
sand
braided channels
meandering channels
fine sand, silt
silt
anastomosed channels
wash material supply dominated channels
Increasing Channel Gradient
Decreasing Channel Stability
Increasing Sediment Calibre
Increasing Spawning and Rearing Habitat Quality
Decreasing Spawning and Rearing Habitat Quantity

FIGURE 5 *Conceptual pattern of morphological types of large channels (from Hogan and Ward 1997, originally from Church 1992, as modified from Mollard 1973 and Schumm 1977).*

divide (Figure 6). As distance increases, the amount of water, channel size, and water force increases, while bed-material sizes and overall channel gradient are reduced. As a result, streams range from those with steep-gradient, step-pool, channels to those with low-gradient, meandering, pool-riffle systems. Pool-riffle morphologies will not occur in steep channels (where gradients exceed 4%), and step-pool morphologies will not be found in low-gradient, large channels.

Forestry activities within a watershed directly and indirectly influence several of the factors listed above. For example, timber harvesting and road building can change flood characteristics, particularly by increasing peak flows (Jones and Grant 1996; Whitaker 2001), increasing sediment delivery (Jordan 2001), altering riparian vegetation (Bird 2001; Millar 2001), and disturbing channel integrity (B.C. Ministry of Forests and B.C. Ministry of Environment 1996a and b). The importance of each factor differs regionally. For example, in coastal areas the most important influence is usually on coarse-textured sediment and on debris production and delivery to the stream. Changes in flood flows and generation of fine-textured sediments are often the main concerns in interior zones where snow accumulation and melt patterns, and soil conditions, can be strongly influenced by logging practices.

Changes in streamflow, sediment, and debris supply cause channels to undergo a sequence of morphological change; increased supply generally leads to aggradation, while decreases in supply commonly lead to channel degradation. Each aggradation and degradation cycle involves many changes in the channel, including altered bed, banks, and LWD conditions. Although many channel responses are similar in each type of channel, there are also important differences between each type. The response of each channel type (RP, CP, and SP) is shown schematically in Figure 7 and summarized in Table 2.

The CAP is based on identification of the channel type and state of disturbance. Operationally, completing a CAP involves both aerial photographic interpretation (if the streams are large enough to be seen on the photo) and field inspections. The drainage network is delineated into homogeneous reaches and these are then analyzed. In the field there are only four measurements required to determine the channel type; these are bankfull channel width and depth, the size of bed sediment commonly moved during the annual high flows, and stream-channel gradient. Field inspections are then conducted to identify the type and extent of channel disturbance. This leads to the assessment of channel state (level of aggradation or degradation).

Several misconceptions seem to be associated with the CAP. By far the most important involves the prerequisite background of the individual conducting the CAP, and identification of the cause of the documented channel state. The CAP states clearly on page 1 (B.C. Ministry of Forests and B.C. Ministry of Environment 1996a) that extensive field experience and academic training in fluvial forms and processes is required to competently complete a CAP. This is essential because the CAP explicitly does not attribute a cause to the identified channel disturbance; there is no mechanism in the CAP to distinguish between logging-induced and natural flood impacts. It is the responsibility of the hydrologist/geomorphologist to interpret the results of the CAP, and any other features thought to be important, to determine the cause of the channel disturbance. It is the individual's training that allows correct interpretations of cause to be made.

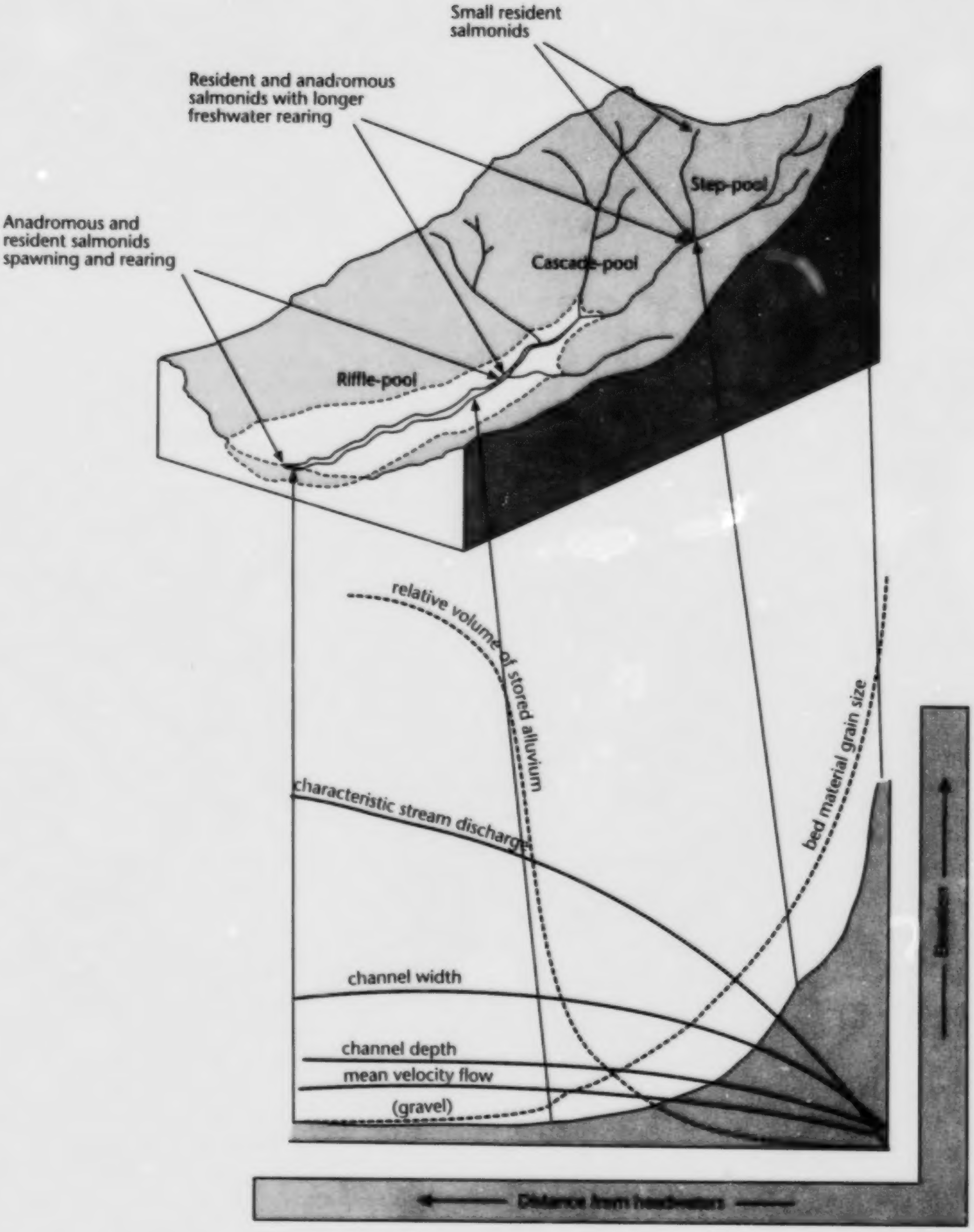

Small resident salmonids
Resident and anadromous salmonids with longer freshwater rearing
Anadromous and resident salmonids spawning and rearing
Step-pool
Cascade-pool
Riffle-pool
relative volume of stored alluvium
bed material grain size
characteristic stream discharge
channel width
channel depth
mean velocity flow
(gravel)
Elevation
Distance from headwaters

FIGURE 6 *Schematic diagram of channel properties within a watershed (Hogan and Ward 1997).*

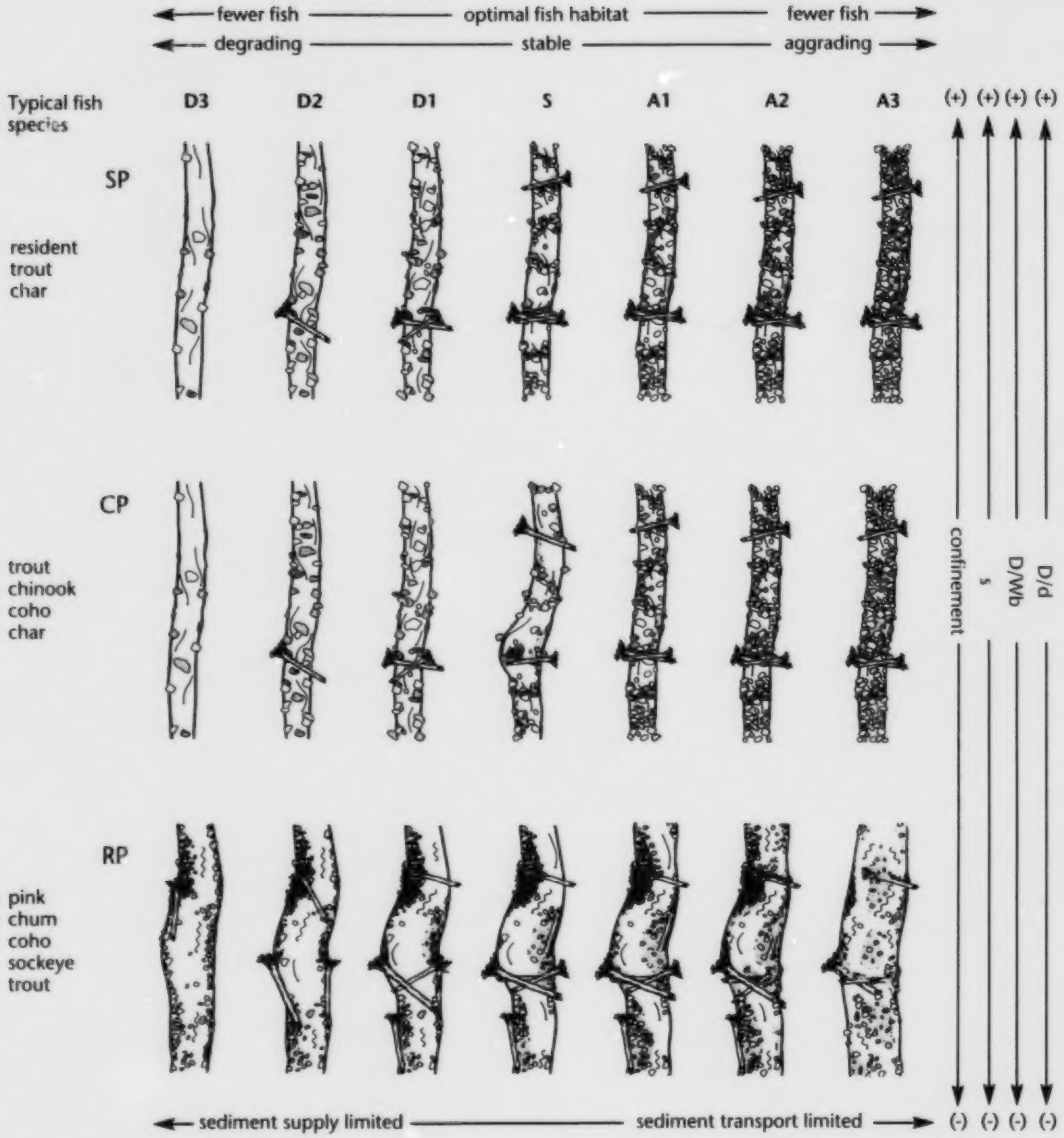


FIGURE 7 *Channel morphology matrix showing levels of disturbance (modified from B.C. Ministry of Forests and B.C. Ministry of Environment 1996b).*

TABLE 2 *General descriptions of stable and disturbed channels (from Hogan and Ward 1997)*

Channel type *Attribute*	**Degraded**	**Stable**	**Aggraded**
Step-pool			
Morphology	• No organized stone lines (due to erosional displacement)	• Intact stone lines: - clast steps - intervening pools	• No organized stone lines (due to depositional in-filling)
Bed sediment	• Largely bedrock	• Largely moss covered	• Not moss covered
Bank sediment	• Not eroded	• Boulder, bedrock, turf, or roots	• Banks cleaned of moss but not eroded (due to bedrock)
LWD	• Not important	• Present, minimal function	• Not important
Cascade-pool			
Morphology	• Stone line series disorganized (no recognizable pattern, due to erosional displacement)	• Series of repeating stone lines forming overall steep zone connecting lower-gradient pools that are $\geq 1W_b$ in length	• Few distinct pools. Deeps in-filled with sediment (both stones originally in lines and finer materials)
Bed sediment	• Large stones remaining (strewn over bed) not moss covered	• Moss-covered stone steps	• All sediment along the bed devoid of moss or vegetative cover
Bank sediment	• Boulder and cobble	• Boulder and cobble	• Boulder and cobble, localized bank erosion
LWD	• LWD not present; if so it has no (minimal) functional role	• LWD present and functioning to limited extent (forms steps, traps/scours sediment, and protects banks)	• LWD present but not functional (does not trap/scour sediment in any substantial way
Riffle-pool			
Morphology	• Extensive riffles and bars	• Repeating riffle-bar-pool sequences	• Extensive riffles and runs
	• Small shallow pools (due to erosion of riffle crests)	• Diverse pool size, shape, and depth	• Small, shallow pools (due to depositional in-filling)
	• Channel consists of less than 1/4 pool, approximately	• Channel consists of 1/2–3/4 pool environment	• Channel consists of less than 1/4 pool, approximately
	• One main channel (primarily single thread)	• One or two main channels	• Multiple channels on braided bed surface
	• Simple, uniform riffle and run shapes	• Diverse riffle shapes	• Simple, uniform riffle and run shapes (minimal depth variability)
	• Limited side channel bar	• Mainly diagonal and point bars	• Mainly mid-channel bars. Bars elevated to, at, or above elevation of surrounding bank tops. Steep downstream bar faces
Bed sediment	• Mainly cobbles and coarser textures	• Cobble and gravels.	• Mainly gravel and finer textures
Bank sediment	• Mainly cobbles and gravel	• Mainly cobbles, gravel, and sand	• Mainly gravels, sand, and cobbles
	• Banks primarily sloping and/or overhanging	• Large proportion of undercut/overhanging banks	• Extensive bank erosion (commonly complete absence of undercut banks)
LWD	• Limited; those present are small and oriented parallel to the banks	• Oriented across, and spans, the channel	• Absent or buried. LWD present are small and oriented parallel to the banks

LADYBIRD CREEK, AN INTERIOR EXAMPLE

A channel assessment has been completed in Ladybird Creek, a watershed located on the north side of Arrow Lake near Castlegar (Figure 8). The entire watershed drains 15 862 ha and includes two main sub-basins (Norns and Matt creeks). The CAP was undertaken in September 1997. This example is included to illustrate the type of stream-channel information available to the hydrologist conducting an IWAP.

Although the final summary of the CAP for Ladybird Creek and its internal sub-basins is directly useful to the hydrologist (Table 3), much of the background information is also informative, particularly as support for channel-restoration prescriptions. The longitudinal profile (Figure 9) illustrates several types of information critical to channel assessment. First, the channel reaches are shown along with the associated morphology. Second, the location of cutblocks and roads are shown in relation to the individual reaches. Third, the reach-averaged level of disturbance is included. Fourth, and most importantly, the location of significant sediment delivery to the channel is plotted. In total, the longitudinal profile incorporates most of the factors important to channel assessment. The hydrologist can review the longitudinal profile to consider the linkage of the individual channel branches. This should include consideration of sediment transfer (transport or depositional) zones and the potential to move sediment downstream into environmentally sensitive areas.

Additional information can be gained by considering the individual disturbance indicator values instead of the grouped summaries. For example, Reach 9 (located in Ladybird North, see Figure 9) is assessed as being slightly aggraded. The occurrence and spatial extent of individual indicators for Reach 9 are shown in Figure 10. The disturbance of this reach is associated with extensive bars (S4), extensive riffles (C1), multiple channels (C4), and dysfunctional LWD (D2). These attributes are both occurring frequently along the reach and are spatially extensive. Elevated bars (C3) are frequent but not spatially extensive (i.e., many small features as opposed to infrequent but spatially large mid-channel bars). The WAP hydrologist can interpret these data in terms of sediment supply, transport, and other hydrological processes. The stream-channel–restoration manager should consider these disturbance indicators in a watershed context. For instance, are there watershed processes (e.g., mass-wasting events) that are influencing channel conditions (e.g., extensive bar surfaces with multiple channels)?

Outputs from the CAP have relevance to other disciplines as well. The expert opinion of many provincial fisheries biologists was solicited to indicate the importance of channel-disturbance level and quality of habitat used by various fish species and different life-cycle phases (Figure 11). There is a clear degradation of habitat quality in all channel types as the channel is subjected to changes in state (increases and/or decreases in channel disturbance).

SUMMARY

The CAP is completed as one component of the WAP. The CAP was designed to be objective and repeatable; it is based on well-established assessment protocol, and, because it is based on fundamental geomorphic processes that

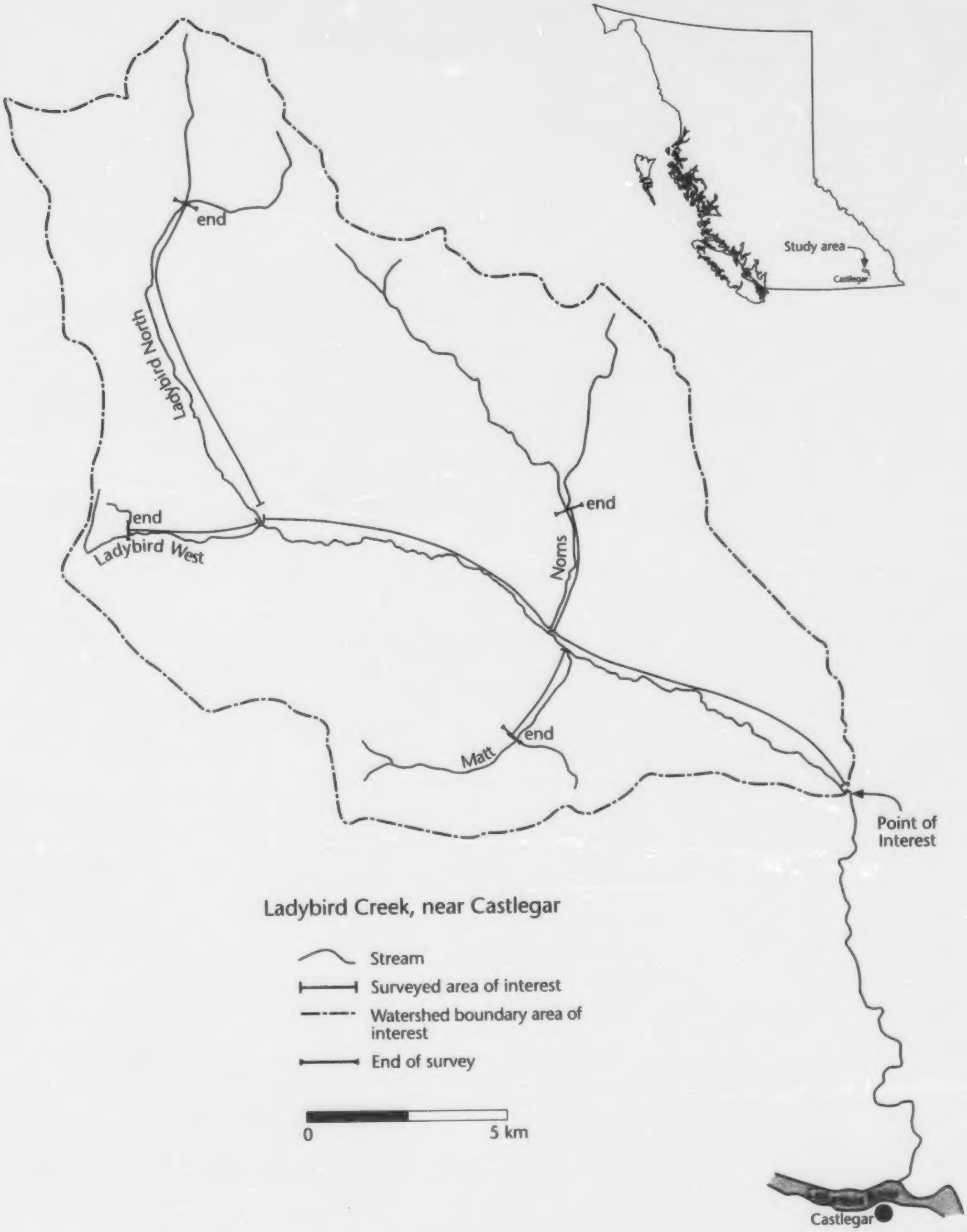


FIGURE 8 *Location map of Ladybird Creek.*

TABLE 3 *CAP summary for Ladybird Creek*

Watershed	Sub-basin	Channel impact
Ladybird	Main	Low, with localized moderate and high
	Norns	Low
	West	Low
	North	Low

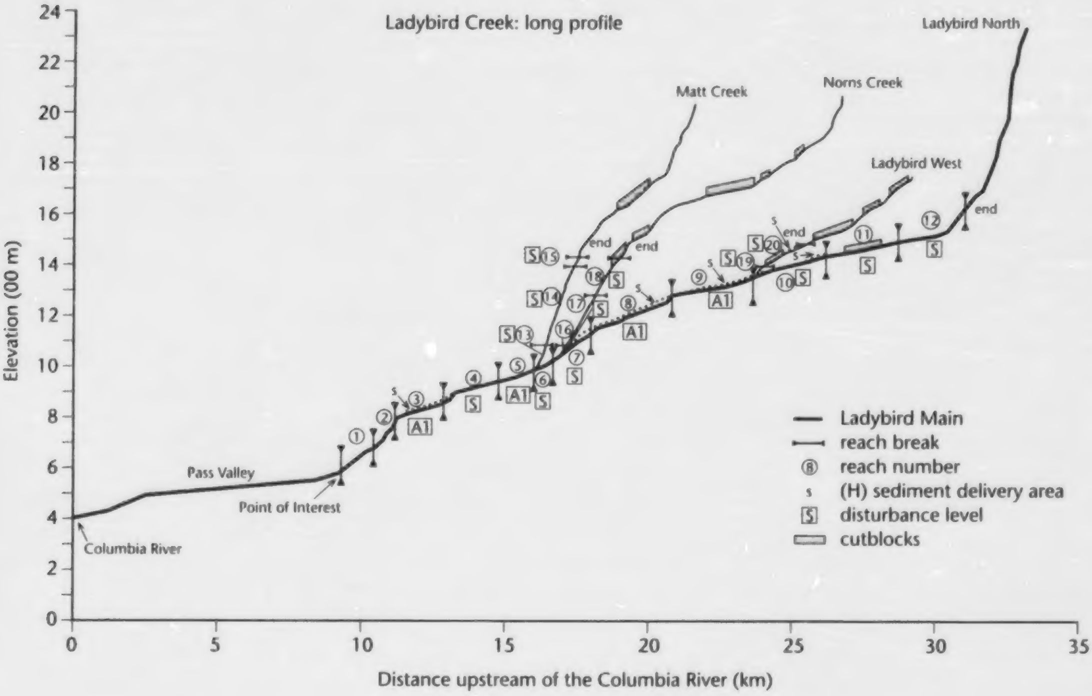


FIGURE 9 *Longitudinal profile of Ladybird Creek.*

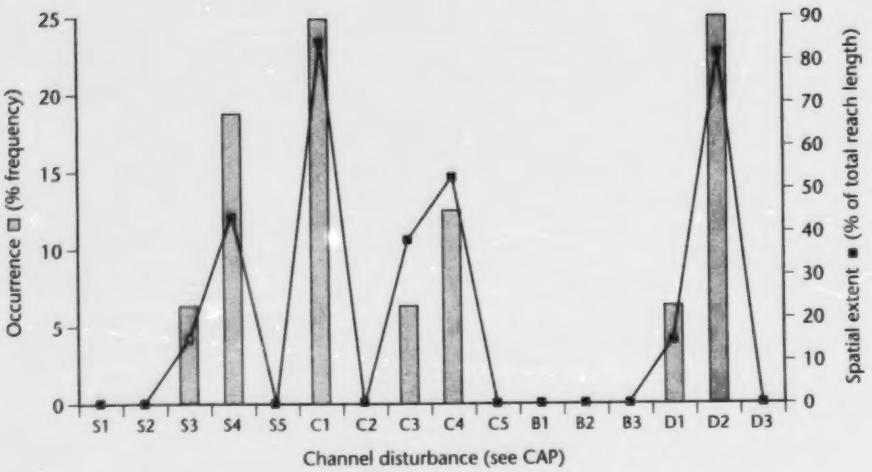


FIGURE 10 *The occurrence and spatial extent of channel disturbance indicators for Reach 9 of Ladybird Creek. The disturbance symbols are detailed in B.C. Ministry of Forests and B.C. Ministry of Environment 1996b); indices with an "S" relate to sedimentological attributes, "C" relate to channel morphology, "B" relate to bank characteristics, and "D" relate to* LWD *functions.*

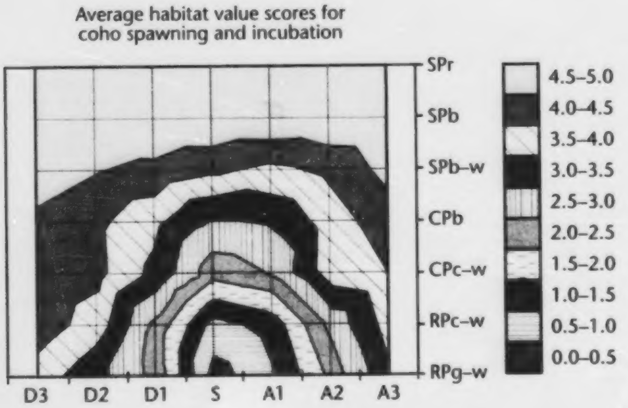


FIGURE 11 *Results from a panel of experts convened to link channel type and disturbance states to habitat values for a range of fish species and life-stage histories (*ESSA *1998).*

operate in a watershed, it is applicable to both coastal and interior areas of the province. The CAP is to be completed by a hydrologist with extensive background experience in fluvial geomorphology. This is important if the cause of documented channel disturbances is to be correctly identified. When the CAP results are available, the hydrologist has several pieces of information important to understanding the hydrology of the watershed. The hydrologist has:

- an inventory of the channel types found in the watershed; each channel type has a different inherent sensitivity to disturbance.

- an inventory of the channel state for each channel type; the frequency and spatial extent of each disturbance indicator is compiled.
- an accompanying geo-referenced inventory of disturbance indicators, which allows the experienced hydrologist to link watershed processes and channel conditions to determine the cause of the disturbance.
- CAP data that are directly relevant to fish habitat studies.
- CAP data that can form the basis for determining correct watershed restoration prescriptions.

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Streamside Logging and Riparian Hazard Assessment in Step-pool Streams

S.A. BIRD

ABSTRACT

A riparian assessment is usually completed as part of the Interior Watershed Assessment Procedure (IWAP). The riparian assessment focuses on the role of riparian vegetation and woody debris in maintaining channel stability and channel structure, and on how this role has been affected by logging. This paper evaluates the effectiveness of riparian assessment procedures in identifying channel disturbance in step-pool streams.

The procedure relies on the identification of indirect channel impacts from riparian logging. Indirect impacts include the loss of bank cohesion following decay of the riparian tree-root network, and the lack of large riparian trees available to the channel from overbank sources. The effects of indirect impacts may not be fully apparent in the channel for several decades and not observed until the riparian area has partially recovered, and this may confound the assessment. Overview assessment procedures designed to identify channel impacts from streamside logging should focus on direct channel impacts. These tend to occur from operating machinery in or across the stream channel, operating machinery on top of banks, salvaging logs out of the active channel, and delivering logging debris to the channel from surrounding hillslopes or valley bottoms.

1 INTRODUCTION

The Interior Watershed Assessment Procedure (IWAP) guidebook (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) is used throughout the interior of British Columbia to help develop watershed-level management recommendations that prevent or mitigate cumulative hydrologic effects from past and/or proposed forest harvesting. In turn, these recommendations are used to assist in the preparation of a forest development plan. The procedure focuses on the assessment of hydrological impacts, including the role of riparian vegetation and wood debris in maintaining channel stability and channel structure, and how this role has been affected by logging. Although streamside logging is no longer permitted within community watersheds or adjacent to fish-bearing streams, the IWAP must consider the effects of any streamside logging that occurred prior to adoption of current regulations and logging along any non–fish-bearing tributaries to larger fish-bearing streams.

The IWAP is designed for application in watersheds with a drainage area ranging from 5 to 500 km^2. Throughout mountainous regions of British Columbia, individual sub-basins selected for assessment are typically steep and often characterized by step-pool stream channels. However, most operational guidelines designed to assess the effects of streamside logging have been derived from research completed on relatively low-gradient, riffle-pool streams (e.g., Toews and Moore 1982; Hogan 1987). The objectives of this paper are to describe patterns of channel disturbance following streamside logging in step-pool streams and then compare rates of channel recovery with rates of riparian forest recovery. Examples are drawn from British Columbia and surrounding regions. These results are then used to test the assumption that the current condition of the riparian area has some predictive value in estimating channel conditions, on an operation level, as part of an IWAP in steepland watersheds.

2 STREAMSIDE LOGGING AND CHANNEL STABILITY

Streamside logging can affect the stability of sediment stored along the banks and in the bed of a stream channel. Direct effects of streamside logging will result from operating machinery in or across the channel, operating machinery on top of banks, salvaging logs out of the active channel, and delivering logging debris to the channel from surrounding hillslopes or valley bottoms. These effects are usually evident in the channel immediately following logging operations. Indirect effects include the loss of bank cohesion following decay of the riparian tree-root network, and a lack of large riparian trees available to the channel from overbank sources. These effects may not be fully apparent for several years or even decades. The nature of these effects is twofold. First, stored sediment may be mobilized as stable storage elements such as bars and banks are disturbed. Second, streambank logging can alter the large woody debris (LWD) budget of a stream by changing the size and amount of LWD pieces delivered to the channel. These are considered below.

2.1 Sediment Mobilization

In riffle-pool streams, the removal of riparian vegetation can lead to bank retreat and transfer of sediments from the riparian area into the active channel (e.g., Roberts and Church 1986). Millar (this publication) shows the dependence of channel planform on dense, deep-rooting streamside vegetation, and how a meandering gravel bed river can be transformed into a braided river following streamside logging. Additional sediment may be released from storage as logs are salvaged from the channel. Once delivered to the channel, these sediments may promote additional bank attack as flow is deflected into the stream-banks.

These effects may not be as apparent in step-pool streams. For example, riffle-pool streams are often bound by alluvial banks and are susceptible to erosion, while step-pool streams are often bound by boulders supported in a matrix of relatively fine sediment between occasional outcrops of bedrock. These streams are less sensitive to bank disturbance by machinery and/or the loss of the riparian tree-root network and are less likely to mobilize additional sediments from the channel margin following streamside logging (with the exception of LWD removal and the subsequent dislodgement of sediment stored in an upstream wedge). Pronounced bank retreat and/or changes in channel planform are not an expected outcome of streamside logging adjacent to a step-pool stream.

2.2 LWD Budgets

Streambank logging can alter the LWD budget of a stream by changing the size and amount of LWD pieces delivered to the channel (Toews and Moore 1982; Hogan 1987). These changes can occur if the transfer of large trees from the riparian area to the channel is interrupted following logging operations. These changes can also occur if existing LWD pieces are salvaged from the channel and/or logging debris is delivered to the channel during logging operations. Overall, this results in a reduction in the size of LWD in the channel or staged to enter the channel. Small, individual debris pieces are less effective in promoting scour or in storing sediments and this generally results in reduced channel complexity (Hogan 1987).

In the absence of any post-logging landslides, logging debris will usually enter the stream channel during or immediately after logging operations (e.g., Toews and Moore 1982). Generally, logging debris contains slash, bark, and LWD pieces with detached root wads that are easily floated downstream at high flows and can accumulate into log jams. Newly formed log jams, especially those formed with logging debris, are usually effective sediment traps and relatively impermeable to sediment transport (see review by Hogan et al. 1998). Upstream of a jam, bed aggradation reduces local channel gradient and promotes the accumulation of fine-textured sediments, and causes the streambanks to erode as the channel widens. Stable sequences of riffles and pools are replaced by extensive riffles as pools are in-filled. Downstream of a jam, the channel becomes coarse textured and can be scoured down to bedrock as sediment supply is restricted from upstream.

Bryant (1980) investigated the development of log jams following streamside logging in a riffle-pool stream in southeast Alaska (results are summarized in Figure 1). Historical channel maps of Maybeso Creek show the presence of several small log jams consisting of large individual debris pieces prior to logging. During streamside logging operations, logging debris was delivered to the channel and then floated downstream during high flow,

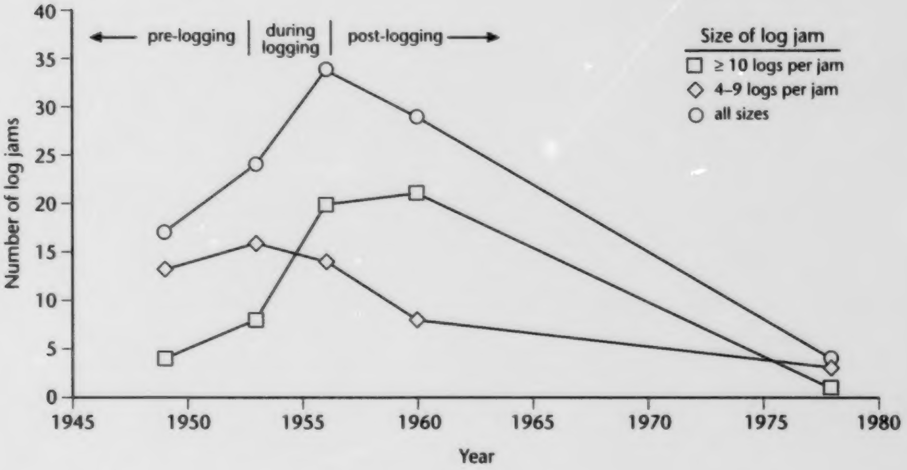

FIGURE 1 *Number of log jams in Maybeso Creek, southeast Alaska, before, during, and after logging. Period of observation spans 1949–1978. Data of Bryant (1980).*

where it accumulated into either new log jams or on top of existing log jams. The overall frequency of log jams initially increased after logging, with most logging debris stored in relatively large log jams. However, most of these structures did not persist in the channel. A decade after logging, the channel was dominated by still large but less frequent log jams. By 1978, both the frequency and the size of individual log jams decreased below pre-logging levels as increasing amounts of LWD were transferred overbank or to downstream reaches. In some cases, the channel was forced around a jam entirely and into the riparian area as the channel aggraded (i.e., the channel avulsed), while in other cases logging debris destabilized existing jams and these eventually broke apart. Only jams that pre-dated logging operations remained in the channel. Hogan (1987) reports similar results from a paired watershed study of riffle-pool streams on the Queen Charlotte Islands. Several decades after streamside logging, the number of sites (log jams and log steps) with significant volumes of stored sediment decreased; however, the total volume of sediment stored at these individual sites increased. Both Bryant (1980) and Hogan (1987) suggest that these changes result in an overall reduction in channel stability as large accumulations of sediment stored behind logging debris are more likely to fail during high flows than their unlogged counterparts, and this can lead to a sudden and widespread redistribution of channel sediments.

Bird (2000) considered this pattern of channel response in three small step-pool tributaries to Blueberry Creek, near Castlegar. Logging debris was observed in these channels (LWD with saw-cut ends) and the overall size of individual LWD pieces stored in the channel decreased. During high flows, some of the more mobile logging debris appeared to have been floated downstream where it was able to accumulate into a new log jam or on top of an existing log jam. However, shortly after logging (<10 years), the size of log jams decreased, although the frequency of log jams increased (as expected) and a greater proportion of LWD was stored in log jams. The relative mobility of logging debris in the channel appears to be an important consideration when determining channel response to streamside logging. For example, headwater channels of Blueberry Creek were relatively narrow compared to the riffle-pool streams noted previously, and large boulders, bedrock outcrops, and confined sections of channel reduced the mobility of logging debris. Most logging debris could be transported only a relatively short distance before being impeded by the channel boundary, preventing the development of large accumulations of debris.

The jams described by Bird (2000) were relatively small but still caused significant channel disturbance as the channels aggraded (e.g., steps were broken apart and replaced with relatively long cascades). This did not destabilize the channel in the same way as described by Hogan (1987), as the failure of any one structure would release only a relatively small amount of sediment and this would be buffered by another structure immediately downstream of the one that failed. However, these structures are still less resilient to major floods. For example, one reach of Blueberry Creek had been logged prior to a major flood (return period >50 years). The channel lacked functional LWD, and logging debris was not identified. It was assumed that the flood likely washed away most of the logging debris in the same manner as that described by Bryant (1980).

The riparian hazard assessment described in the first version of the IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1995) involved a simple tally of the total length of stream logged to at least one streambank. A scoring system was used to rank disturbance based on several criteria weighted by the overall proportion of logged streambanks in a sub-basin or watershed. In the first major revision of the IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1998), the riparian hazard assessment described a procedure modified after the Riparian Assessment and Prescriptions Procedures (Konning 1999). The procedure involved an overview assessment, based on riparian vegetation type, that described the "potential function" associated with the stand structure of the riparian forest. The potential level of riparian functioning included parameters that consider consequences to the channel, including bank stability and delivery of LWD to the channel. Stand structure was categorized based on a qualitative assessment that described both the species and the age distribution of the riparian canopy. The current version of the IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999) simply requires that the professional completing the assessment consider the role of riparian vegetation and LWD in maintaining channel stability and structure, and how this role has been affected by logging.

Bird (2000) compared the results from both overview and detailed channel surveys, designed to identify the effects of streamside logging on channel conditions, against the result of the IWAP riparian hazard assessment (B.C. Ministry of Forests and B.C. Ministry of Environment 1998). Field work was undertaken in headwater reaches of Blueberry Creek and Little Cayuse Creek near Castlegar, and in Gold Creek near Cranbrook. Results of the hazard assessment are shown in Figure 2. Overall, the procedure correctly identified channel impacts from riparian logging when the potential level of riparian functioning was low (e.g., a shrub-herb riparian cover). However, the

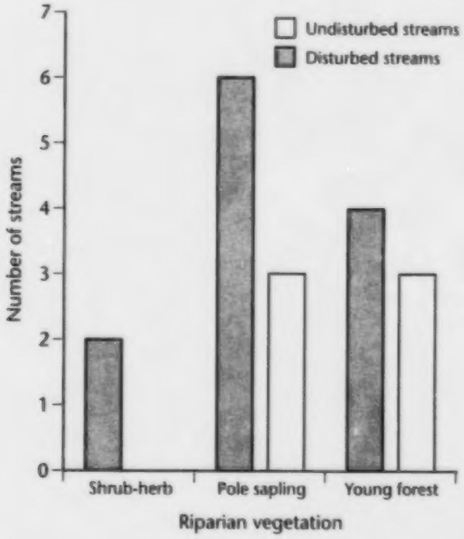

FIGURE 2 *Results of the riparian hazard assessment. Data of Bird (2000).*

procedure was less successful when potential levels of riparian functioning were moderate or high (e.g., pole sapling to young forest cover). For example, Gold Creek contained remnants of an old road crossing, and disturbance has persisted in the channel although the riparian forest has re-established. In this example, Gold Creek was narrow and not capable of transporting the logging debris downstream in the time since logging. Much of this debris will likely remain in the channel until organic decay breaks the material into smaller pieces that can be floated and transported downstream by high flows. Stream power, channel width, and the length of individual pieces of logging debris appear to be important limitations on the ability of the channel to recover from disturbance initiated by streamside logging. Time scales of channel recovery are not necessarily the same as time scales of riparian recovery. These factors should be considered by a riparian hazard assessment.

These results illustrate a limitation of the procedure. The assumption that riparian logging necessarily leads to channel disturbance in step-pool streams, and that the present condition of the riparian area, indicates that channel condition cannot be applied in all circumstances. In many cases, streamside logging can result in channel disturbance, especially if falling occurs across streambanks or if machinery operates in or around the channel. However, if direct disturbance does not occur, then the channel may remain relatively stable until the riparian area recovers. Conversely, when streamside logging has resulted in channel disturbance, recovery of the riparian area does not necessitate the recovery of the channel. Disturbance may persist in the channel for several decades while the riparian area begins recovery soon after harvest. These results suggest that the current condition of a riparian area may have some utility in identifying sites with potential channel disturbance, but it should not be used as a surrogate measure in an assessment.

4 CONCLUSIONS

There is no clear connection between the condition of the riparian area and current channel conditions. Following streamside logging, stable channel conditions were observed with a "pole sapling" riparian area, while disturbed channel conditions were observed with a "young forest" riparian area. In part, the procedure may be confounded because it relies on the identification of indirect channel impacts from riparian logging. Indirect impacts include the loss of bank cohesion following decay of the riparian tree-root network, and the lack of large riparian trees available to the channel from overbank sources. The effects of indirect impacts may not be fully apparent in the channel for several decades and not observed until the riparian area has partially recovered. Overview assessment procedures designed to identify channel impacts from streamside logging should focus on direct channel impacts. These tend to occur from operating machinery in or across the stream channel, operating machinery on top of banks, salvaging logs out of the active channel, and delivering logging debris to the channel from surrounding hillslopes or valley bottoms. These impacts occur regardless of the current condition of the riparian area (e.g., pole sapling, or mature forest).

Procedural recommendations for completing a riparian hazard assessment in both step-pool and riffle-pool streams as part of an IWAP include:

1. Describe the riparian canopy (age, logging history, species composition, cover, etc.) from recent air photos and forest-cover maps on a reach-by-reach basis. Supplemental field observations may be included but should not be required at this stage of the assessment.
2. Describe the morphological setting of the stream reach from terrain maps (if available) and air photos. The morphological setting describes the reach and near-reach environment by landform. Reaches bordered by an erodible floodplain or valley bottom should be considered a priority for field work. Other reaches may be non-alluvial and not influenced by streamside logging. These map and air-photo observations can be confirmed with a limited field inspection.
3. Determine the hydraulic geometry of individual stream reaches. Slope can be derived from topographic maps, while width and depth can be estimated from regional functions of drainage basin area. In some cases, these relations may need to be developed for the IWAP being undertaken and may require field work. Reaches with sufficient stream power to mobilize logging debris, and reaches with sufficient width to allow this debris to be transported downstream and reorganized into jams, should be considered a priority for field work.
4. Determine the magnitude and frequency of post-logging flood events capable of modifying the channel. Flood events should be described in the context of the channel type (e.g., step-pool vs. riffle-pool streams). Reaches with one or more post-logging, channel-forming floods capable of redistributing logging debris should be considered a priority for field work.
5. Determine if one or both channel banks have been logged. This information can be derived from air photos and forest-cover maps and will not normally require field work. Reaches with both streambanks logged should be considered a priority for field work.
6. Estimate the channel type from topographic maps and air photos. Riffle-pool streams are more reliant on bank integrity relative to step-pool channels, and the loss of root cohesion can result in channel disturbance.
7. Focus any field work in reaches where riparian vegetation plays an important role in maintaining a stable channel form. Riparian vegetation is most effective in streams that can modify their boundary and erode channel banks, and in streams that can reorganize any LWD delivered to the channel (e.g., alluvial or semi-alluvial streams where LWD plays a functional role in maintaining channel morphology).
8. In the field, identify impacts of streamside logging. These include:

- Logging debris in the channel (e.g., branches, tree tops, bark, small logs, and LWD with saw-cut ends).
- Upturned root wads along the banks (blowdown) that have disturbed the streambanks or have delivered sediment from the root wad to the channel.
- Simplified channel conditions (i.e., the channel lacks morphological complexity).
- A lack of functional and/or stable LWD.
- Accumulations of small, unstable LWD pieces and logging debris that form jams.
- Increased frequency of log jams initially after logging operations (size of jams depends on mobility of the logging debris).

- Decreased size and frequency of log jams several decades after logging operations.
- Machinery damage to channel banks (e.g., trails or tracks adjacent to collapsed banks).
- An unusually wide section of channel, given its position within a watershed (e.g., lack of root cohesion in the bank materials has increased the rate of localized bank erosion).

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Riparian Logging and Channel Stability

ROBERT G. MILLAR

ABSTRACT

Recently developed theory is used to derive a simple planform stability diagram. The stability diagram is based on the threshold between meandering and braiding rivers, and includes a friction angle parameter that can be used as a surrogate to quantify the stabilizing influence of riparian vegetation. The planform stability diagram can be used as a relatively simple screening tool to determine the sensitivity of a particular river or stream to riparian logging. The necessary parameters are channel slope (S), bankfull or mean annual discharge (Q), and the median bank grain diameter (D_{50}). Given that direct riparian logging is now forbidden under the Forest Practices Code, the stability diagram is probably most useful in assessing the current channel condition, and in the case of a wide and unstable channel, to assess whether direct riparian logging represents a significant factor in the current channel condition.

1 INTRODUCTION

The effects of logging activities on sediment load and peak discharges have received considerable attention. Less emphasis has been directed towards the effects of riparian logging and its influence on channel stability, despite evidence that it can be significant (e.g., Beeson and Doyle 1995). The main difficulty has been, first, to quantify the influence of riparian vegetation on bank stability, and, second, to determine the effect of reduced bank stability on channel morphology (American Society of Civil Engineers 1998). Some recent advances in this area (Millar and Quick 1993; Millar 2000) are discussed in this paper, and some implications of this work for British Columbia forest practices and channel assessment procedures are also discussed. A theoretical analysis will be presented, which can be used to derive a simple planform stability diagram. It is proposed that this stability diagram can be used to identify those rivers and streams that rely on riparian vegetation for stability, and that are inherently sensitive to changes in riparian vegetation.

Riparian vegetation can increase the stability of bank sediment by:

1. reducing the near-bank velocity and effective bank shear stress;
2. increasing the bank strength through binding of the sediment by root masses; and
3. enhancing interstitial deposition of fine washload sediment.

Because of the difficulty in adequately quantifying the influence of bank vegetation on channel morphology, its effect has not been explicitly considered in any previous formulations for the meandering-braiding transition slope S^*. However, it is proposed that by using a method developed by Millar and Quick (1993), riparian vegetation strength can be quantified in terms of the bank friction angle, ϕ', which can then be readily incorporated into quantitative analyses.

The bank stability algorithm used by Millar and Quick (1993) is based on tractive force method for stable channel design developed by the U.S. Bureau of Reclamation (Lane 1955). In the USBR relation, ϕ' is the angle of repose of the noncohesive bank sediment, which approaches an upper limiting value of about 40° for coarse gravel. Millar and Quick (1993) modified the original relation in order to account for the stabilizing influence of bank vegetation:

$$\frac{\tau_{bank}}{\gamma(s-1)\,D_{50}} \leq 0.048 \tan\phi' \sqrt{1-\frac{\sin^2\theta}{\sin^2\phi'}} \qquad (1)$$

where

τ_{bank} = reach-averaged bank shear stress,
(Pa); γ = unit weight of water,
(N/m^3); s = specific gravity of bank sediment,
D_{50} = median sediment diameter (m), and
θ = bank angle (°).

The coefficient 0.048 in Equation 1 is related to the critical dimensionless shear stress for the bank sediment.

The two key independent variables related to bank stability are D_{50} and ϕ'. The value of D_{50} is assumed here to be the same for both the bed surface and bank sediment, which is generally reasonable for gravel banks, but is not valid where banks are silt or fine sand. This assumption is necessary in order to derive a relatively simple relation for S^*. The value of ϕ' in Equation 1 can varied from a minimum value of about 40°, which indicates little influence from bank vegetation, up to a maximum value approaching 90° in order to account for the stabilizing influence of bank vegetation.

Millar and Quick (1993) developed an analytical model that was used to investigate the influence of bank stability and bank vegetation on the hydraulic geometry of gravel-bed rivers. The model was calibrated using data from Andrews (1984) and Hey and Thorne (1986) in order to provide an estimate of ϕ' for each river. This involved using different trial values of ϕ' until an agreement was forced between the modelled and observed channel width, *W*. The rivers in the Andrews (1984) and Hey and Thorne (1986) data sets are described as stable, single-thread (meandering) channels. Andrews (1984) has subjectively stratified the data into *thin* and *thick* bank vegetation classes.

Similarly, Hey and Thorne (1986) had stratified their data into four classes from vegetation type I, grass with no trees or bushes, to vegetation type IV, with >50% trees and bushes. Differences in the type and density of bank vegetation appear to explain much of the variation in the values of ϕ'. Despite a wide range of calibrated ϕ' values from each vegetation class, the mean values of ϕ' increase consistently with bank vegetation density (Table 1).

The friction angle ϕ' represents a lumped calibration parameter that probably accounts for several different processes, including reduction of near-bank velocity and shear stress, binding of the bank sediment by root networks, packing and imbrication, and cementing of the gravel clasts by interstitial fines. Direct accounting of each of these processes would be difficult and complex. The proposed use of ϕ' permits bank vegetation and other effects to be readily quantified in terms of a single parameter. This approach is analogous to the use of Manning's n to characterize hydraulic roughness. Although a relation between ϕ' and subjective vegetation "density" has been shown (Table 1), this relation is not a simple one, and the value of ϕ' is probably species dependent, and more closely related to rooting depth, and strength and density of the root network.

3 THEORETICAL MEANDERING-BRAIDING TRANSITION CRITERION

The classic paper on river channel patterns by Leopold and Wolman (1957) contains the well-known empirical relation for the meandering-braiding transition:

$$S^* = 0.013Q^{-0.44} \qquad (2)$$

where
S^* = transition slope that separates meandering from braided rivers, and
Q = bankfull discharge (m^3/s).

Braided rivers tended to have slopes greater than S^*, while the meandering rivers have flatter slopes. Other investigators have derived similar empirical relations to Equation 1, but with different values for the coefficient and exponent (see Bridge 1993 for a recent summary).

Despite being widely cited in the literature, Equation 2 does not perform particularly well as a predictor of meandering and braiding when applied to independent field data from gravel-bed rivers. The principal limitation of it is that it does not consider the influence of bank stability on S^*. Using an analytical model, Millar (2000) developed the following theoretical relation for the meandering braiding transition:

TABLE 1 *Summary of ϕ' values obtained through model calibration of each vegetation class*

	Data source	Andrews (1984)		Hey and Thorne (1986)			
	Vegetation type	Thin	Thick	I	II	III	IV
ϕ' (°)	Mean	37.5	51.6	39.9	43.7	48.0	55.6
	Range	29.3–46.3	42.7–58.8	20.1–51.7	30.1–58.8	32.0–72.0	36.3–79.1
	n	14	10	12	16	13	20

$$S^* = 0.0002 D_{50}^{0.61} \phi'^{1.75} Q^{-.25} \qquad (3)$$

where
D_{50} = median sediment diameter for the banks and bed surface (m),
ϕ' = bank sediment friction angle (°), and
Q = bankfull discharge (m^3/s).

This relation overcomes the main limitations of Equation 2 because it includes the parameters D_{50} and ϕ', which define the bank stability. This theoretical relation was able to discriminate between meandering and gravel banks with varying densities of bank vegetation (Millar 2000).

4 CASE STUDY: ANALYSIS OF SLESSE CREEK

Slesse Creek is a mountain stream straddling the Canada-USA border in southwestern British Columbia. It represents an interesting case study of a stream that has transformed from a relatively narrow and stable sinuous planform, to a wide and unstable braided morphology. The observed transformation can be attributed to a reduction in the stability of the banks following streamside clearcut logging. Detailed description is given by MacVicar (1999).

Slesse Creek is a fourth-order stream with a total drainage area of 170 km², of which approximately 100 km² of the upper watershed is located south of the Canada-USA border in Washington State. It flows through a glaciated valley, flanked by steep hillslopes with gradients in excess of 1:1. Upper reaches are largely confined by bedrock, while in the lower reaches north of the Canada-USA border a narrow alluvial plain has developed. Remnant glacial boulders and bedrock vertically control the slope of the channel.

The upper catchment south of the Canada-USA border is pristine forest preserved within the Mount Baker Wilderness Area. On the Canadian side, logging to the streambanks occurred during the 1950s and 1960s. Figure 1 shows the condition of the channel approximately 2 km north of the Canada-USA border prior to logging (1940), and subsequent to logging (1993). In 1940 the channel was sinuous or irregularly meandering, with an average width of approximately 30 m. Bank vegetation in 1940 would have consisted primarily of mature, old-growth coniferous forest. By 1993, the channel had widened to approximately 150 m, and had developed a braided morphology. Current bank vegetation consists of sparse, deciduous trees and bushes. The watershed upstream of the study site is essentially pristine, and one can therefore assume that the discharge and sediment supply would not have changed appreciably from pre-logging levels. The transformation in planform morphology is attributed to a reduction in the stability of the banks following logging. It represents a good opportunity to test the theoretical braiding criterion developed herein.

Discharge records from a hydrometric station downstream indicate a mean annual flood of approximately 92 m³/s (MacVicar 1999), which is assumed equivalent to the bankfull discharge, Q. Pebble counts from two representative bank and bar surfaces returned a value of $D_{50} = 0.13$ m. The current slope of the reach, obtained from maps and field surveys, is approximately 0.02, and does not appear to have changed appreciably over pre-logging conditions. Using these values of Q, D_{50}, and S with the

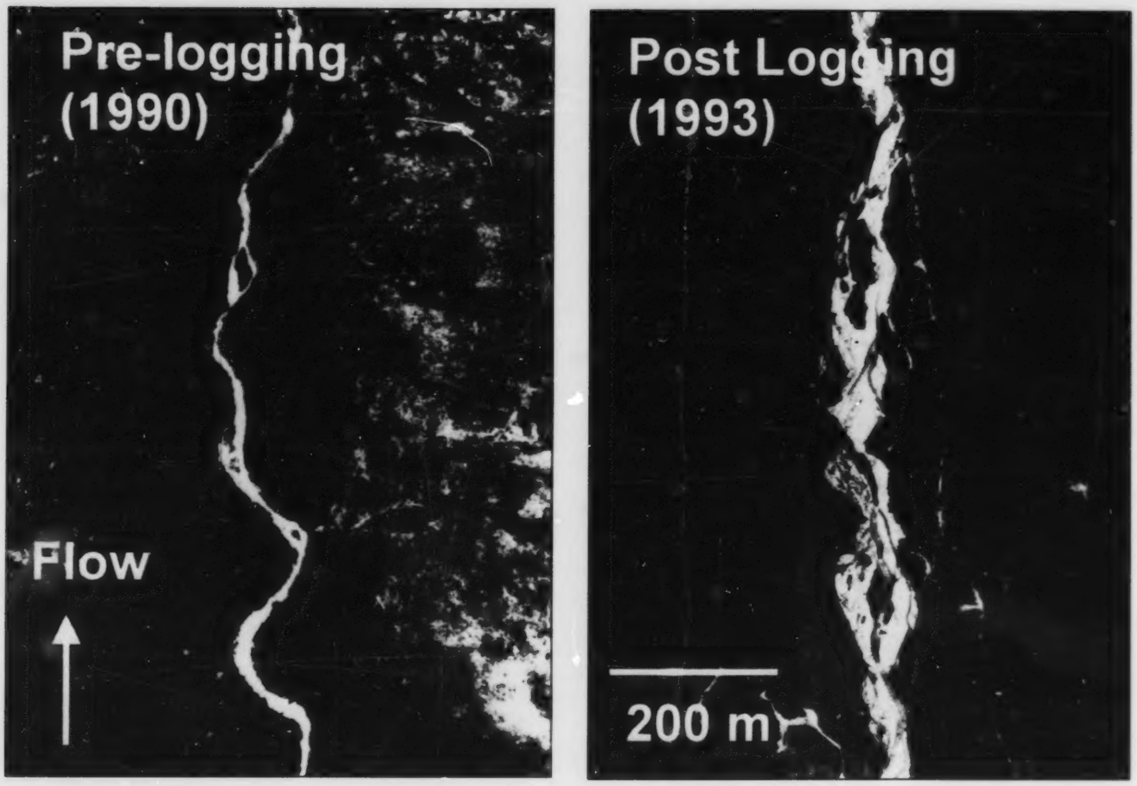

FIGURE 1 *Slesse Creek approximately 2 km north of the Canada-USA border.*

hydraulic geometry model (Millar and Quick 1993) and solving for the range of values 40° ≤ ϕ' < 90°, yields a solution curve that indicates the variation of W with ϕ' (Figure 2). Each point on the solution curve represents an optimal solution. Figure 2 can be used to estimate the appropriate pre-logging value for ϕ', and to confirm the presumed post-logging value of $\phi' = 40°$. For a 1940 pre-logging channel width of 30 m, an estimate of $\phi' = 70°$ is obtained by interpolation (Figure 2). Assuming a post-logging value of $\phi' = 40°$, which would be expected in the absence of significant bank vegetation, an optimum width of about 120 m is predicted. This is somewhat less than the observed width of 150 m, but is considered a reasonable agreement because the hydraulic geometry model does not account for bars and islands. It does indicate that the effect of streamside logging on erodibility of the banks can be reasonably represented by a reduction in the value of ϕ' from about 70° to the limiting value of 40°.

Given the reduction in the value of ϕ' following logging, equation (3) can be used to determine the effect on the theoretical value of S^*. The pre- and post-logging values for Q, W, D_{50}, S, and ϕ' are summarized in Table 2. Of the independent variables Q, D_{50}, and ϕ', only ϕ' has changed significantly. The value of S has remained more or less constant at 0.02. The corresponding values of S^* calculated from equation (1) for both the pre- and post-logging conditions are also shown, together with the predicted and observed planform morphology (meandering or braided). The effect of reducing ϕ' from 70° to 40° following logging results in a decrease in the value

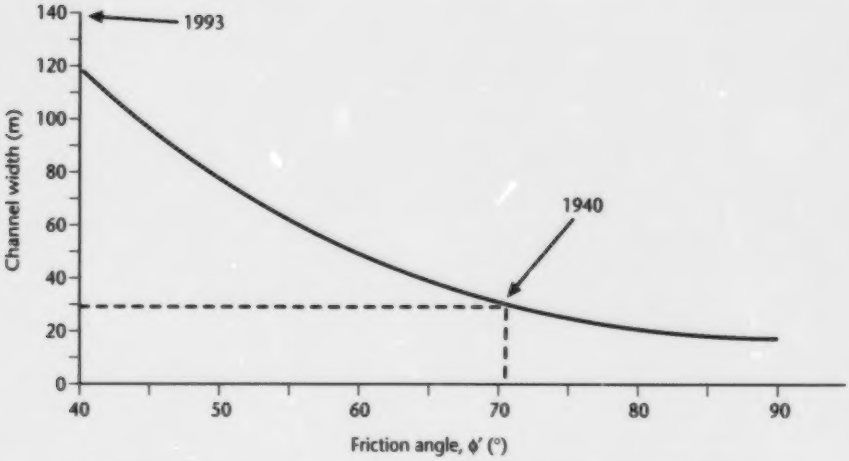

FIGURE 2 *Slesse Creek solution curve showing the variation of channel width with ϕ′.*

TABLE 2 *Summary of pre- and post-logging parameters for Slesse Creek*

Year	Q (m^3/s)	W (m)	S	D_{50} (m)	ϕ′ (°)	S^*	Predicted	Observed
1940	92	30	0.02	0.13	70	0.032	M	M
1993	92	150	0.02	0.13	40	0.012	B	B

M = meandering. B = braided.

of S^* from 0.032 to 0.012. The theory predicts that a meandering channel ($S < S^*$) would have existed under pre-logging bank stability conditions, whereas a braided channel ($S > S^*$) would develop following a post-logging reduction in bank stability. This is in agreement with observation.

5 PLANFORM STABILITY DIAGRAM

Field observations suggest that the magnitude of planform response to changes in bank vegetation varies greatly, with some rivers being relatively insensitive (Trimble 1997), whereas others may undergo complete planform metamorphosis (Mackin 1956). Slesse Creek is one example of a river that is highly sensitive to changes in riparian vegetation. A stability diagram has been developed by plotting S versus $D_{50}^{0.61}Q^{-0.25}$ (Figure 3), which allows equation (3) to be plotted using values of ϕ′ consistent with sparse or ineffective riparian vegetation (40°), and for dense and well-developed, deep-rooting species (70°). This divides the field into three regions, and sensitivity of river planform to changes in the bank vegetation can be readily determined from its plotting position. Rivers that plot in Region I are predicted to be relatively insensitive to changes in riparian vegetation, and would develop a single-thread or meandering channel irrespective of the type and density of the bank vegetation. Rivers that plot in Region II are potentially the most sensitive to changes in the character of the bank vegetation.

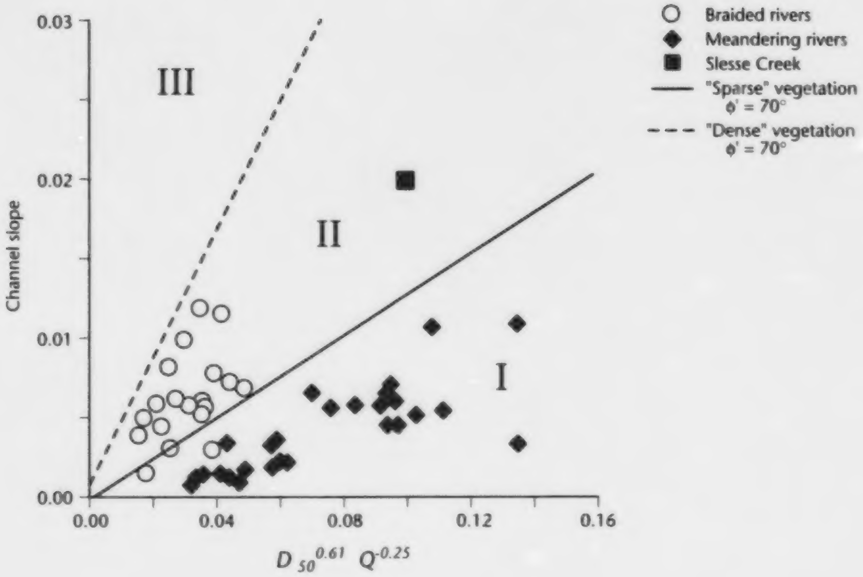

FIGURE 3 *Planform stability diagram.*

If the banks are in a sparsely vegetated state, or when shallow-rooting, ineffective species dominate the riparian zone, a wide and shallow braided channel would be expected. Meandering channels could exist only where banks had developed high values of ϕ' that are consistent with dense or deep-rooting riparian species. Changes in the type and calibre of bank vegetation would have the potential to completely alter channel planform. Clearing of vegetation along banks of meandering rivers that lie in Region II would cause destabilization and widening, and potentially metamorphosis to a braided channel. Rivers that plot in Region III are likely to remain braided irrespective of the condition of riparian vegetation.

6 IMPLICATIONS FOR CHANNEL ASSESSMENT PROCEDURES

The planform stability diagram (Figure 3) can be used as a relatively simple screening tool to determine the sensitivity of a particular river or stream to riparian logging. The necessary parameters are channel slope (S), bankfull or mean annual discharge (Q), and the median bank grain diameter (D_{50}). Those rivers that plot in Region I well below the curve for sparse vegetation ($\phi' = 40°$) would be least sensitive to direct riparian logging, while those that plot above that curve in Region II would potentially undergo a metamorphosis from meandering to a braided planform.

Given that direct riparian logging is now forbidden under the Forest Practices Code, Figure 3 is probably most useful for assessing the current channel condition, and in the case of a wide and unstable channel, for assessing whether direct riparian logging represents a significant factor in the current channel condition.

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Effects of Forest-harvest Rates on Stream-channel Changes in the Central Interior of British Columbia

PIERRE G. BEAUDRY AND ALLEN GOTTESFELD

ABSTRACT

The study investigates the relationship between the level of forest harvesting within 12 medium-sized watersheds and the change in stream-channel width over time. Stream-channel widths and sediment sources were measured from a chronosequence of rectified aerial photographs, dating back to the early 1960s. During the period between the mid 1960s and 1984 most of the study reaches evolved towards narrower channels. During the period between 1984 and the mid 1990s most of the watersheds experienced an increase in average channel width. No statistical relationship could be established between the level of forest harvest and the increase in channel width. Decadal variations in climate appeared to best explain the variability in the observed increases in stream-channel width during the late period.

INTRODUCTION

Forest-harvesting activities have the potential to alter a variety of natural processes within a watershed. For example, activities that remove the trees and vegetation in a watershed can lead to increased water flows (Bosch and Hewlett 1982; Jones and Grant 1996). Road networks often cause increased inputs of fine sediments (Madej 1982), and higher peak flows (Jones and Grant 1996). Landslides increase the amount of both coarse and fine sediments, and harvesting close to channel banks can decrease the amount of coarse woody debris in the stream and cause bank instability (Naiman et al. 1992). A river's response to land-use activities can be quite complex; however, it can often be detected from changes in the shape and features of the stream-channel bed (Ryan and Grant 1991).

In areas where fine gravel and sand are readily available as potential bedload, channel filling, channel widening, and bar instability are a common response to forestry activities such as road-building and forest-harvesting (Knighton 1984). Increases in both the water and sediment supply to a stream channel typically cause the channel to become wider, shallower, straighter, and steeper (Schumm 1971; Leopold 1994). If the stream channel is large enough, many of these changes can be mapped over time using chronosequences of aerial photographs (Sedell and Froggatt 1984; Hogan and Schwab 1990; Ryan and Grant 1991; Gottesfeld 1997; Ham and Schwab 1998).

It is generally believed that the more extensive the clearcut logging is in a watershed, the greater will be the level of negative impacts on certain characteristics of stream-channel morphology, such as stream-channel width (Knighton 1984). The main focus of this study is to investigate the effects of the level of forest-harvesting in a watershed on changes to stream-channel width of medium-sized watersheds in central British Columbia.

STUDY AREA

General Geographical Location

Twelve sub-drainages of the Willow and Bowron watersheds were randomly selected for this study. Four of the drainages are located in the Willow watershed and eight drainages are located in the Bowron watershed (Figure 1). The Bowron River and Willow River are adjacent watersheds located east and southeast of Prince George and are 3403 km^2 and 3206 km^2, respectively. They occupy part of the Fraser Basin and Fraser Plateau areas described by Holland (1976). The headwaters of the watershed are located in the Quesnel Highlands and are bordered to the east by the Cariboo Mountains and Columbia Mountains. The landscape is characterized by moderate to steeply rolling hills ranging in elevation from 1200 to 1500 m, with a few higher mountains up to 2000 m. The main valleys are wide, and slope at less than 2%. Both watersheds have experienced extensive harvesting in the past 35 years (Beaudry and DeLong 1996; Berris 1997).

Regional Hydrology

In the region near Prince George, floods typically result from snow melt, or from rain on the melting snowpack, and occur between late April and early June. In small watersheds, floods may also result from intense, late-summer rainfall. The study streams are ungauged; however, long-term gauging records have been collected by the Water Survey of Canada (WSC) near the mouths of the Willow (08KD006), Bowron (08KD003), and Cariboo rivers (08KH003). These records provide general information about the hydrology of the region (Figure 2). A frequency analysis of the records for the Bowron and Willow rivers was used to assign return periods to the various annual floods (Northwest Hydraulic Consultants 1998) (Figures 3 and 4). Nearly all of the maxima are nival floods. In the Willow River, only the event of 1964 (25 September) was not associated with spring snow melt. In the Bowron River, only four events were not snow-melt generated; these were 15 October 1958, 26 September 1964, 15 September 1969, and 29 October 1973. Barkerville, at an elevation of 1265 m, is the nearest climate station with long-term records. Here, precipitation is distributed fairly evenly throughout the year, and totals about 1000 mm (Figure 5). The maximum, recorded, daily rainfall occurred in September (69.9 mm), though daily precipitation exceeding 50 mm has been recorded in most summer months.

METHODS

Study Objectives

The objective of this study is to investigate the effect of "level of harvest" on changes to stream-channel width. In this study we define "level of harvest" simply as the cumulative amount of forest-harvesting in a watershed at a

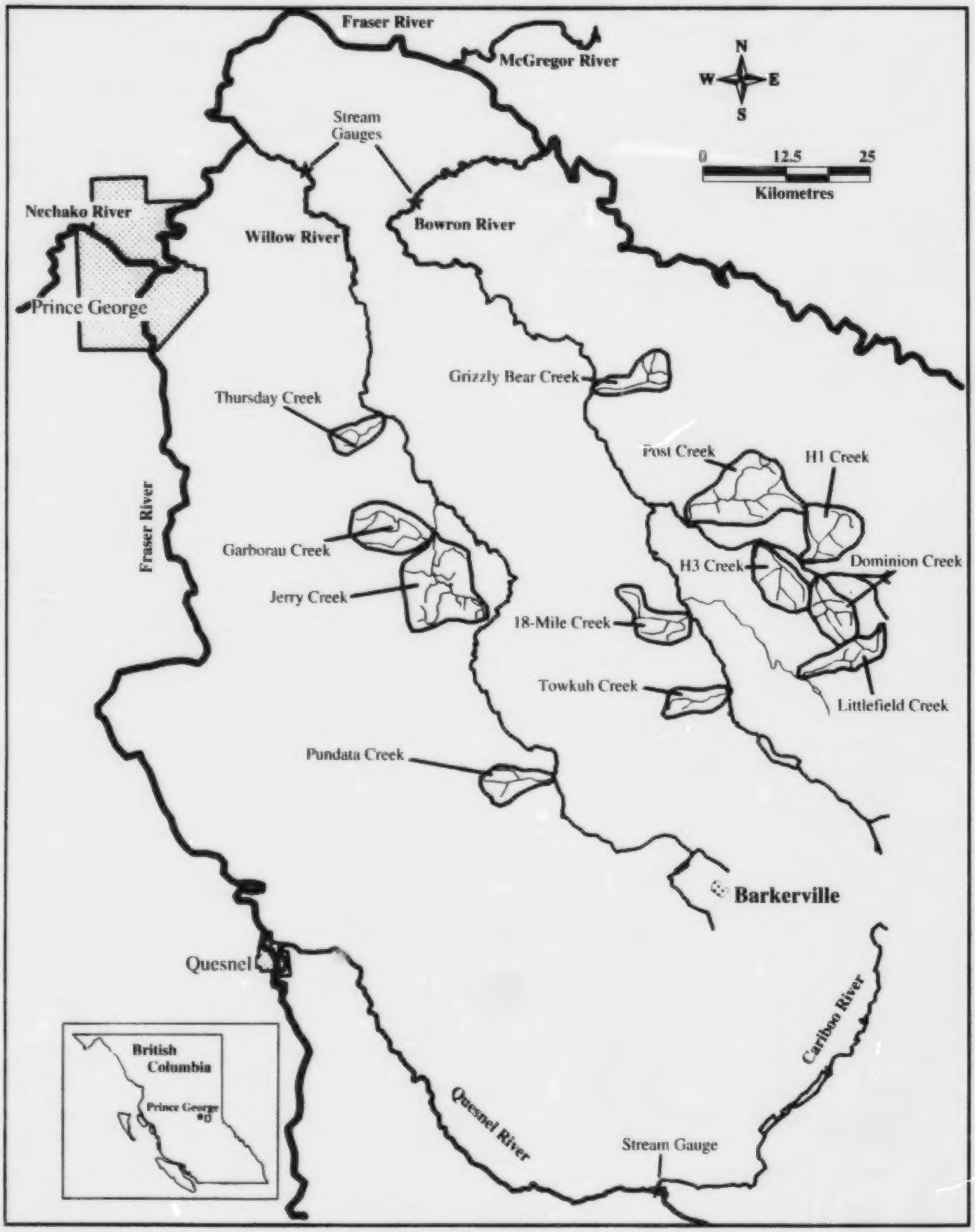

FIGURE 1 *Geographic distribution of the study watersheds.*

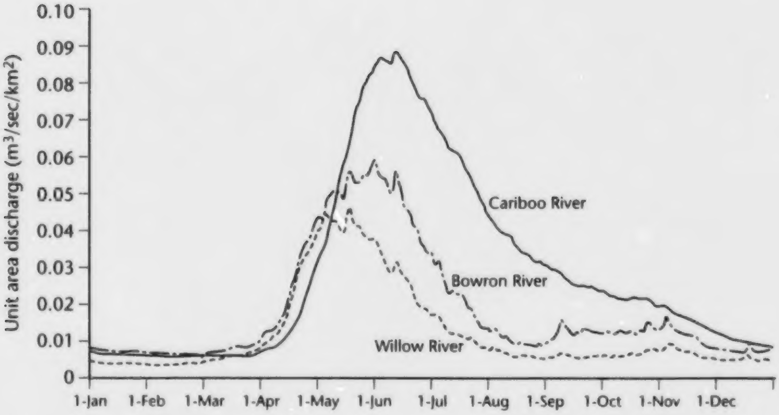

FIGURE 2 *Unit area hydrographs of average daily flows for Bowron, Willow, and Cariboo rivers.*

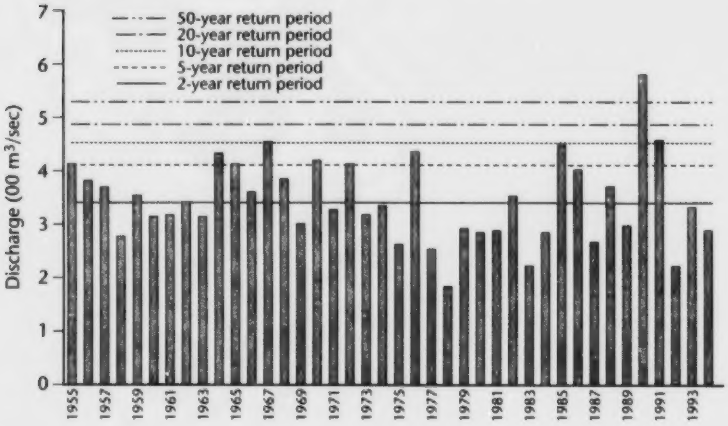

FIGURE 3 *Annual maximum daily flow and flood frequencies for the Bowron River below Box Canyon.*

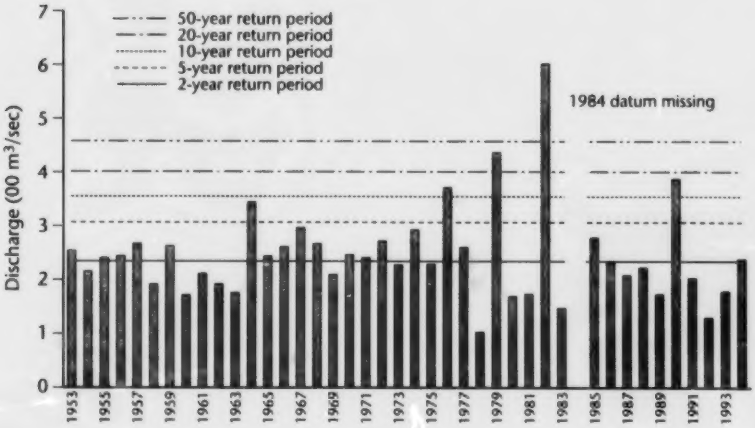

FIGURE 4 *Annual maximum daily flow and flood frequencies for the Willow River above Hay Creek.*

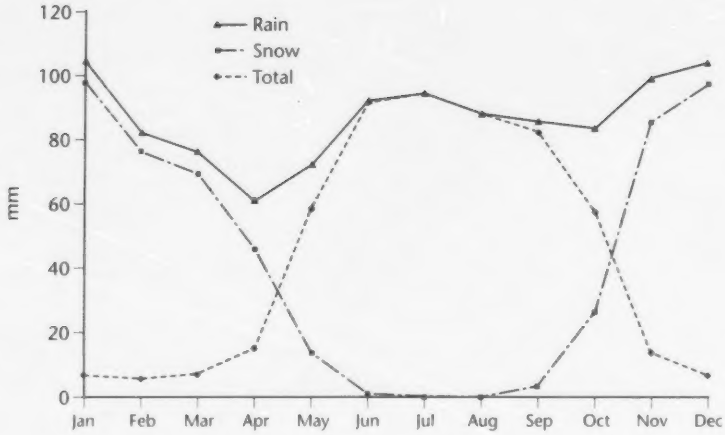

FIGURE 5 *Average monthly precipitation at Barkerville climate station.*

given time, expressed as a percentage of the watershed. Considering landforms as a whole, river channels are quite sensitive elements, at least in certain dimensions such as channel width (Knighton 1984). Seemingly, channels can adjust to changed land-use conditions, at least in the width dimension (Knighton 1984). Stream-channel width is a relatively easy planimetric property to measure from historical air photographs, and is not as dependent on stage height as are other channel properties—such as extent of gravel bars or islands.

Consequently, we decided that average stream width was the most appropriate variable to investigate in this study.

The hypotheses to be tested are as follows:

Ho = The "level of harvest" does not affect stream-channel width.
H1 = The "level of harvest" has a significant effect on stream-channel width.
The significance level is set at $\alpha=0.05$

Watershed Selection

We identified 48 sub-drainages in the Bowron and Willow watersheds that were suitable for this project. These sub-drainages ranged in size between 20 and 120 km^2, and had a variety of logging histories, geological conditions, and topographic conditions. In an attempt to get a balanced experimental design and an even distribution of the independent variable (i.e., "level of harvest"), we stratified our population of 48 watersheds into three levels of harvest: 1) "low harvest," which was defined as ≤13% of the watershed harvested in 1994, 2)"moderate harvest," which was defined as >13% and ≤30% of the watershed harvested in 1994, and 3) "high harvest," which was defined as >30% of the watershed harvested in 1994. Within each of these three stratified groups we randomly selected four watersheds to obtain an experimental sample of 12 watersheds.

Stream-channel Measurements

Detailed measurements of the stream-channel planimetric characteristics were made on a chronosequence of rectified aerial photographs for the 12 study watersheds (Northwest Hydraulic Consultants Ltd. 1998). The channel mapping was limited to the lower (partly alluvial) stream reaches where the channel can alter its morphology. The selected air photographs and TRIM maps were reviewed to select the stream length for mapping. These generally included the lower 3–10 km of mainstem stream channel, or about one-third of the total main channel length.

In each watershed, the length of channel chosen for mapping was divided into homogeneous reaches. Reach breaks were placed at distinct changes in stream-channel gradient, changes in channel pattern, junctions with major tributaries, or at entrances and exits of canyons. Typically, the mapped section of stream contained three to five reaches. A total of 49 reaches were mapped for the 12 watersheds.

The photogrammetrist controlled the historic air photo from the NAD83 TRIM control, which was coordinated from 1:60 000 British Columbia government photography dated 1984. Typically, TRIM control was transferred from one set of coverage to another, to an accuracy of about ± 0.1 mm at photo scale. The pooled error between any two points is ± 0.14 mm, which, for a typical spacing of about 100 mm between control points, produces a scale error of 1 part in 700, or about 0.1%. This is insignificant when compared to the inaccuracy introduced by poor-quality air photographs, or to the difficulty in accurately mapping boundaries of mature vegetation (Northwest Hydraulic Consultants Ltd. 1998).

The photogrammetrist states that the stream-channel boundaries can be accurately mapped within one- or two-tenths of a millimetre at map scale (1:5000). Assuming that the channel boundaries are mapped to an accuracy of ± 0.2 mm at map scale, then the pooled error in the channel width is ± 1.4 m on the ground. On this basis, if channel widths from one year of mapping to the next differ by less than this value, it is possible that the difference results from control errors rather than from changes in channel width. The quality of the data extracted from the photos was judged sufficiently accurate for the purpose of measuring and comparing changes in channel width.

Channel-width Variability

For each study stream, average channel widths over all the mapped reaches were calculated for each year of mapping. The average minimum channel width in each watershed was used to space points every seven channel widths along the thalweg (i.e., line of greatest depths), for the most recent year of maps. Channel width was then measured perpendicular to the flow at each of these points. The points were then transferred to the other maps, and the channel width was re-measured for the other years at the same point. The averages of these measurements, for each reach, are the values used for the statistical analysis. All of the reaches from three of the 12 watersheds initially selected were rejected, along with a few additional reaches from the other nine watersheds. These were rejected because the channels were too narrow, making the relative errors of the width measurements unacceptable. A total of 27 reaches, with acceptable data, remained for the analysis.

Sediment Source Inventory

The amount of sediment delivered to a stream channel can play a large role in shaping the channel because the channel must respond to the amount of water and sediment it transports. In this project, sediment sources greater than 0.25 mm^2 (or 0.5 x 0.5 mm) on the air photos, were measured and classified and then marked onto 1:20 000 TRIM maps in each of the study areas. The length and width of each sediment source was converted to a disturbed area in hectares using the nominal scale of the air photograph, corrected for elevation. The sediment sources were coded by the date when they first were visible on the photographs, by their watershed and tributary number, and also assigned a source number. Each source was then classified by type, location, land use, deliverability, and size.

Statistical Analysis

We used regression analysis to determine if there was any statistical relationship between the "level of harvest" in the watershed (independent variable) and the percent change in width (%ΔW) of each study reach (response variable) for two time periods ($\alpha = 0.05$). The "early period" represents a period of about 20 years between the mid 1960s and the mid 1980s. The "late period" represents a period of about 10 years between the mid 1980s and the mid 1990s. Because the air photos were not all flown on the same dates, the time spans for both of these periods are not identical for all watersheds. Table 1 provides the dates covered by each of the periods for the nine retained study watersheds.

Since the duration of the two periods is substantially different, there was a concern that the concept of "average annual change" in channel width was not necessarily the most appropriate variable for this analysis. The value of "average annual change" was obtained by dividing the total change in width by the duration of the period (17–20 years for the early period, and 4 and 10 years for the late period). Since it is unlikely that the changes occur gradually and evenly over the years, the use of "average annual change" may be misleading in a situation where the duration of the different periods is so variable. Consequently, we also examined the absolute change in channel width for each of the periods, for each of the study reaches.

Limitations of the Study Design

In retrospect, several limitations have been identified with this study design. These are presented here so that the reader is aware of the inherent limitations of the study. These limitations are as follows:

1. For many of the small reaches in this study, the air-photo resolution is not sufficiently adequate to precisely measure the small changes in channel width that occurred.
2. The duration of the "early period" is substantially different than the duration of the "late period." This makes it impossible to compare the changes in channel width over a uniform time period.

TABLE 1 *Dates covered by the "early period" and the "late period" for each of the nine study watersheds*

Watershed	Dates covered by "early period"	Years in "early period"	Dates covered by "late period"	Years in "late period"
Post	22/08/66 to 25/07/84	18	25/07/84 to 10/07/90	6
H1	22/08/66 to 25/07/84	18	25/07/84 to 10/07/90	6
H3	22/08/66 to 25/07/84	18	25/07/84 to 10/07/90	6
Dominion	22/08/66 to 25/07/84	18	25/07/84 to 10/07/90	6
Grizzly Bear	23/08/66 to 25/07/84	18	25/07/84 to 10/07/90	6
Gaboreau	20/06/67 to 24/07/84	17	24/07/84 to 10/07/90	6
Jerry	20/06/67 to 24/07/84	17	24/07/84 to 29/07/94	10
Pundata	15/08/67 to 22/09/87	20	22/09/87 to 16/07/91	4
Thursday	10/09/69 to 25/07/84	20	25/07/84 to 20/07/94	10

3. There is a large variability in watershed characteristics among the study watersheds, despite our attempt to control this.
4. Within each of the two periods studied, the duration of the time span between successive photos is not consistent between watersheds.

All of these limitations are inherent to this type of study. It is very difficult to find 12 homogeneous watersheds within a small geographic area that have a good distribution of desired forest-harvest levels.

DESCRIPTIONS OF STUDY WATERSHEDS

Physical characteristics of the nine study watersheds were generated from 1:20 000 TRIM digital maps and are provided in Table 2. The characteristics of the 28 study reaches are provided in Table 3. The average reach gradient ranges between 0.3% and 4.4% (Table 3). For most of the study watersheds harvested, intensive forest harvesting began in the late 1970s. The exceptions are Thursday Creek, where harvesting began in the early 1960s, and Post Creek, where harvesting did not begin until the mid 1980s (Table 3). Virtually all of the forest harvesting in the study watersheds was done by ground-based systems (either hand falling or mechanical harvesters) and the trees were ground-skidded with rubber-tired skidders. Small, localized patches of timber were hand felled where the terrain was unsuitable for mechanical harvesters. Very limited areas were cable yarded. The history of forest harvesting in the watershed is provided in Table 4. The total amount of forest harvesting in the watershed, at the end of the "late period," ranges from 0% to a maximum of 42.3% (Table 4).

TABLE 2 *Morphological characteristics of the nine study watersheds*

Watershed name	Watershed size (km^2)	Watershed order (from 1:20 000 TRIM)	Stream magnitude (from 1:20 000 TRIM)	% of watershed less that 10% gradient	% of watershed greater than 30% gradient	Basin elevation		Total length of mainstem (m)
						Min (m)	Max (m)	
Grizzly Bear	46.2	4	44	18.5	25.1	779	1 880	13 900
Dominion	48.4	3	38	11.9	37.0	1 090	2 179	14 540
H1	65.1	4	157	9.5	51.7	1 050	2 172	15 160
Pundata	37.4	3	35	34.5	0.7	994	1 637	13 040
Gaboreau	74.4	4	68	43.1	1.7	881	1 780	17 560
H3	51.1	3	35	17.2	28.6	975	1 949	13 760
Post	110.0	4	99	18.6	25.6	858	1 946	26 165
Jerry	118.1	4	138	56.7	1.6	881	1 540	20 880
Thursday	21.8	3	19	24.8	3.1	709	1 563	11 404

TABLE 3 *Characteristics of the 27 study reaches*

Watershed name	Reach identification	Watershed size (km^2)	Reach length (m)	Hillslope coupling[1]	Reach gradient (%) (from 1:20 000 TRIM)	Average reach width (m) (measured using cross-sections on air-photos)		
						Beginning of early period	End of early period and beginning of late period	End of late period
Grizzly Bear	Gri2	46.0	1 572	L	2.4	15.7	10.5	22.7
Dominion	Dom3	47.0	979	H	2.5	14.6	13.7	14.7
	Dom4	45.0	1 568	M	1.8	13.5	13.5	14.4
H1	H1_1	64.1	1 058	M	2.6	13.7	13.3	13.7
	H1_2	63.8	1 775	H	1.8	10.3	10.4	10.4
	H1_3	61.6	1 039	M	2.0	14.8	13.6	13.8
Pundata	Pun1	37.4	2 292	H	3.0	17.4	8.6	16.0
	Pun2	35.0	1 818	M	2.5	33.7	19.1	29.5
	Pun3	32.0	1 620	L	2.4	19.4	12.7	20.5
Gaboreau	Gab1	74.1	4 014	H	1.3	29.4	14.9	11.7
	Gab2	61.2	3 074	L	1.8	20.5	8.8	8.7
	Gab3	40.6	2 612	M	2.0	23.9	13.8	9.6
H3	H3_2	54.1	2 247	M	1.7	27.3	21.5	22.2
	H3_3	44.9	1 009	H	2.5	11.0	9.9	11.7
	H3_4	43.6	2 547	H	2.2	11.6	10.5	10.7
Post	Pos1	110.0	1 009	L	1.2	24.6	24.0	31.3
	Pos2	107.0	2 587	L	1.4	15.5	15.7	17.3
	Pos3	104.0	2 040	M	1.6	13.9	14.9	32.4
	Pos4	99.0	2 819	H	2.1	12.0	12.6	27.7
	Pos5	98.0	1 496	H	1.7	13.1	14.1	20.0
Jerry	Jer1	118.1	1 047	L	0.2	11.9	10.9	9.6
	Jer2	116.2	1 200	L	0.3	9.4	8.5	7.7
	Jer3	113.0	2 856	L	0.3	10.1	7.2	7.2
	Jer4	105.0	2 648	L	0.3	10.0	7.9	7.3
Thursday	Thu2	19.8	1 572	M	3.1	16.8	8.5	13.6
	Thu3	18.0	547	H	2.4	11.5	7.9	9.8
	Thu4	16.5	1 120	L	4.4	20.4	10.4	16.8

[1] Hillslope coupling refers to the average connectivity of the hillslope to the stream channel reach. A "High" hillslope coupling means that sediment generated on the hillslope will generally be delivered directly to the stream channel. A "Low" hillslope coupling means that there is a wide floodplain between the hillslopes and the stream channel, and sediment generated on the hillslope will generally not be delivered directly or immediately to the stream channel. A "Medium" hillslope coupling means that there is a mix of "Highs" and "Lows" in that reach.

TABLE 4 *Forest harvesting history of the nine study watersheds*

Watershed name	Reach-identification	Watershed size (km²)	Biogeoclimatic subzone (in order of spatial importance in the watershed)	% of watershed logged		
				1966	1984	1994
Grizzly Bear	Gri2	46.0	ICHvk2, SBSwk1	0	4.6	11.6
Dominion	Dom3	47.0	ESSFwk1, SBSvk	0	0	0
	Dom4	45.0	ESSFwk1, SBSvk	0	0	0
H1	H1_1	64.1	ESSFwk1, SBSvk	0	0	1
	H1_2	63.8	ESSFwk1, SBSvk	0	0	0
	H1_3	61.6	ESSFwk1, SBSvk	0	0	0
Pundata	Pun1	37.4	SBSwk1, ESSFwk1	0	5.0	13.0
	Pun2	35.0	SBSwk1, ESSFwk1	0	5.3	11.0
	Pun3	32.0	SBSwk1, ESSFwk1	0	5.0	10.6
Gaboreau	Gab1	74.1	SBSwk1	0	12.0	28.0
	Gab2	61.2	SBSwk1	0	7.8	21.0
	Gab3	40.6	SBSwk1	0	1.2	22.0
H3	H3_2	54.1	ESSFwk1, SBSvk	0	10.9	18.9
	H3_3	44.9	ESSFwk1, SBSvk	0	4.9	17.0
	H3_4	43.6	ESSFwk1, SBSvk	0	2.3	15.0
Post	Pos1	110.0	ESSFwk1, SBSvk	0	0	25.0
	Pos2	107.0	ESSFwk1, SBSvk	0	0	23.0
	Pos3	104.0	ESSFwk1, SBSvk	0	0	22.5
	Pos4	99.0	ESSFwk1, SBSvk	0	0	21.0
	Pos5	98.0	ESSFwk1, SBSvk	0	0	21.0
Jerry	Jer1	118.1	SBSwk1	0.5	22.0	38.0
	Jer2	116.2	SBSwk1	0.5	21.0	37.6
	Jer3	113.0	SBSwk1	0	19.0	35.6
	Jer4	105.0	SBSwk1	0	16.0	31.6
Thursday	Thu2	19.8	SBSj1	9.9	28.6	38.0
	Thu3	18.0	SBSj1	10.9	31.5	39.4
	Thu4	16.5	SBSj1	11.6	30.2	42.3

Changes in Stream Width over Time

The change in the average stream width was calculated, for each of the study reaches, for both the "early period" and the "late period." We examined the changes expressed both as: 1) a percentage change per year and 2) a percentage change for the entire period. These were calculated as follows:

"early period" change per year

$$\%\Delta W/Y = (W_{eep} - W_{bep})/ W_{bep} / Y * 100 \tag{1}$$

"late period" change per year

$$\%\Delta W/Y = (W_{elp} - W_{blp})/ W_{blp} / Y * 100 \tag{2}$$

"early period" change per period

$$\%\Delta W = (W_{eep} - W_{bep})/ W_{bep} * 100 \tag{3}$$

"late period" change per period

$$\%\Delta W = (W_{elp} - W_{blp})/ W_{blp} * 100 \tag{4}$$

where

$\%\Delta W/Y$ is the percentage change in average width per year,

W_{bep} is the average width of the reach at the beginning of the "early period,"

W_{eep} is the average width of the reach at the end of the "early period,"

W_{blp} is the average width of the reach at the beginning of the "late period,"

W_{elp} is the average width of the reach at the end of the "late period,"

Y is the number of years in a period, and

$\%\Delta W$ is the percentage change in average width for the period.

The average change in channel width per year ($\%\Delta W/Y$) of each reach and the standard deviation are presented as dot and line plots in Figures 6 and 7. Figures 8 and 9 show the data for the average change in channel width per period ($\%\Delta W$). The data are sorted and presented in order of increasing amount of the watershed harvested as measured at the end of the period in question.

The data presented in Figures 6 and 8 show that there was little change in stream-channel width during the early period. This was irrespective of whether the change was calculated on an annual basis (Figure 6) or over the whole period (Figure 8). It appears from these figures that most of the stream reaches actually decreased in width over the early period.

In contrast to the early period, the changes in channel width during the late period were, for some reaches, quite substantial (Figures 7 and 9). In most cases the stream channels experienced an increase in width during this period. The apparent trend of a decrease in width during the early period and an increase in width during the late period appears to be consistent irrespective of the way the changes are reported (i.e., per year or per period). The amount of change does not appear to be related to the amount of harvest in the watershed.

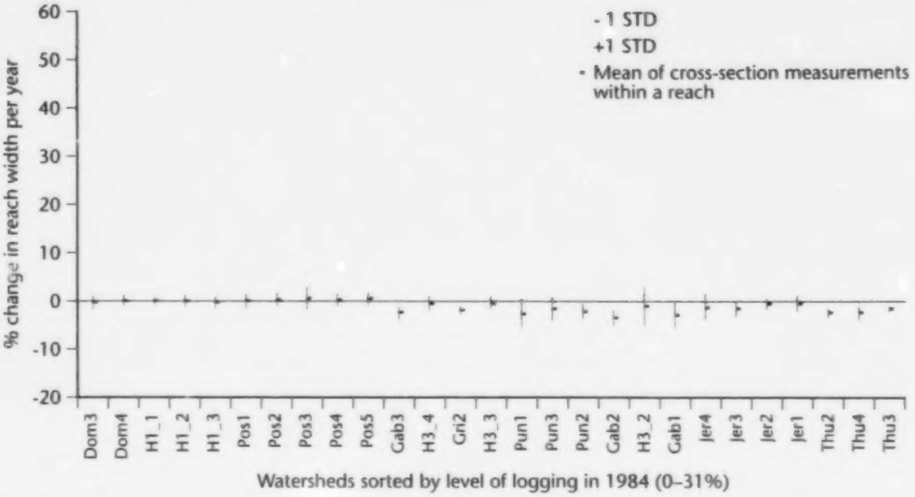

FIGURE 6 *Percentage change in reach width per year and standard deviation for the "early period," sorted by increasing amount of watershed harvested, as measured at the end of the "early period."*

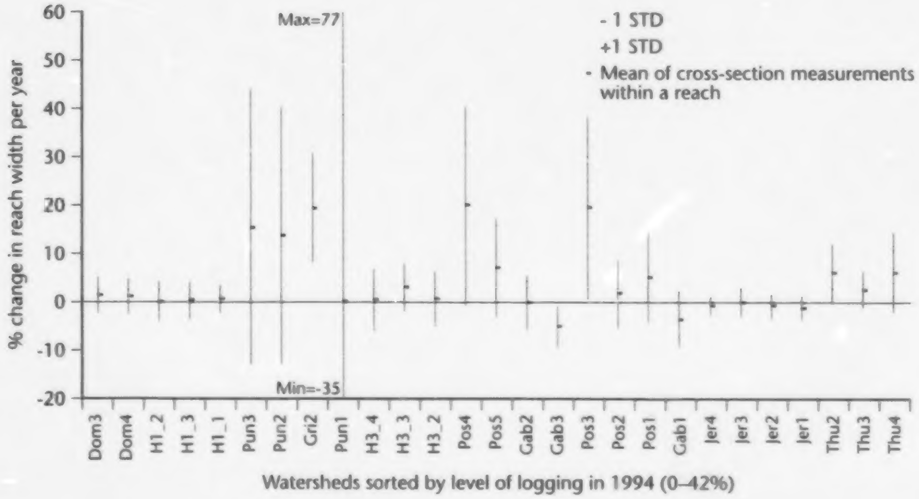

FIGURE 7 *Percentage change in reach width per year and standard deviation for the "late period," sorted by increasing amount of watershed harvested, as measured at the end of the "late period."*

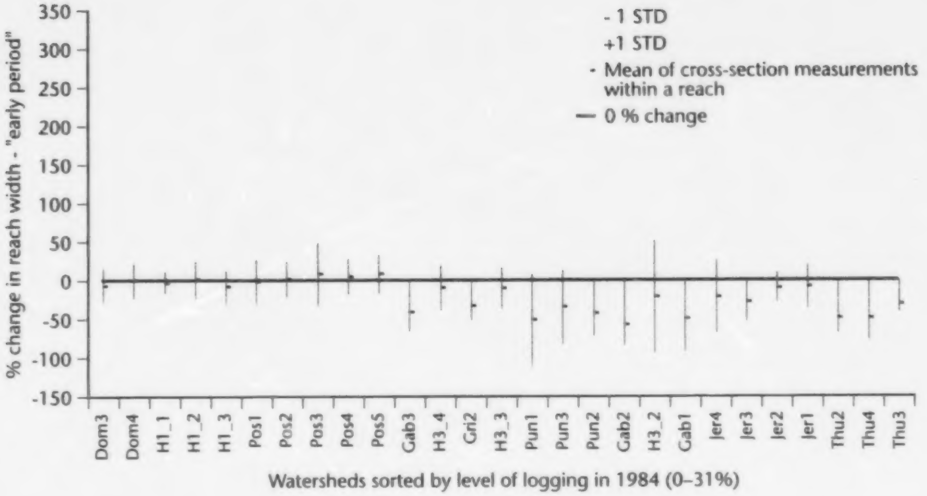

FIGURE 8 *Percentage change in reach width and standard deviation for the "early period," sorted by increasing amount of watershed harvested, as measured at the end of the "early period."*

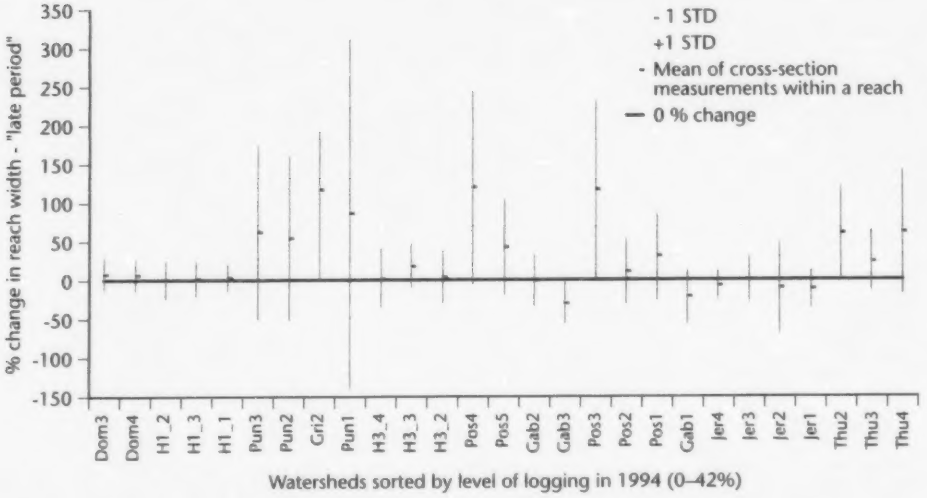

FIGURE 9 *Percentage change in reach width and standard deviation for the "late period," sorted by increasing amount of watershed harvested, as measured at the end of the "late period."*

Changes in Sediment Sources over Time

The changes in the number and nature of sediment sources over time, for the nine study watersheds, are presented in Table 5. The second column provides the total number of discrete sediment sources identified from air photos for each year of the enumeration. The number of sediment sources did not change dramatically over time, in any of the study watersheds, except possibly Pundata Creek. The reduced number of sediment sources in Pundata Creek is the result of the revegetation of a number of small slides and slumps along the channel that were identified in 1967. The third column presents the total number of sediment sources directly coupled to stream channel (i.e., those that deliver sediment directly to the channel). These numbers do not dramatically change over time either, again with the possible exception of

TABLE 5 *Evolution of sediment sources over time for each of the nine study watersheds*

Watershed and year of aerial photography	Number of sediment sources	Number of sediment sources coupled to the stream[1]	Number of sediment sources coupled to the stream and logging[2] related	Number of sediment sources coupled to the stream, logging related, and large[3]
Gaboreau - 1967	13	11	0	0
Gaboreau - 1984	22	19	1	0
Gaboreau - 1990	12	11	1	0
Jerry –1967	0	0	0	0
Jerry –1984	8	0	0	0
Jerry –1994	11	0	0	0
Pundata –1967	11	11	0	0
Pundata –1987	13	13	0	0
Pundata –1991	2	2	0	0
H1 –1966	27	13	0	0
H1 –1984	34	17	0	0
H1 –1990	39	20	0	0
H3 –1966	18	11	0	0
H3 –1984	22	14	0	0
H3 –1990	21	11	2	1
Dominion –1966	40	21	0	0
Dominion –1984	44	24	0	0
Dominion –1990	44	23	1	0
Grizzly Bear- 1966	19	5	0	0
Grizzly Bear - 1984	14	3	0	0
Grizzly Bear- 1990	16	4	0	0
Thursday –1969	5	4	3	2
Thursday –1984	8	5	4	2
Thursday –1994	6	5	3	1
Post – 1966	54	34	0	0
Post –1984	43	21	0	0
Post –1990	36	15	3	1

[1] "Coupled to the stream" indicates that sediment produced from the source is delivered directly to the stream channel.

[2] "Logging related" indicates that the sediment source was most likely created by forest harvesting operations (e.g., clearcuts, roads, trails, gravel pits).

[3] "Large" refers to any sediment sources equal to or larger than 0.05 ha in area.

Pundata Creek. The fourth column presents the number of sediment sources that are a direct result of the forest-harvesting operations and that deliver sediment directly to the stream channel. For all watersheds these numbers are very low. The last column identifies the number of large sediment sources (i.e., >0.05 ha) that are both coupled to the stream and caused by forest-harvesting operations. These numbers are also very low. These data suggest that the direct contribution of forest-harvesting activities to changes in sources of coarse sediment over time was minor. Consequently, the changes in channel width cannot be attributed, to any large degree, to changes in the number of sediment sources.

Variations in Streamflows over Time

Annual peak flows The flood of record in the Willow River occurred in 1982, with another large flood occurring in 1979. These events were assessed as having a return period of greater than 50 years for 1982 and about 30 years for 1979 (Figure 4). During the "late period" there was only one large event recorded in the Willow River. This event occurred on June 13, 1990 and was assessed as having a return period of about 18 years (Figure 4). However, anecdotal information suggests that individual tributary watersheds of the Willow River may have behaved differently than the main river itself during this flood. Several bridges, crossing tributary drainages, were washed away during the June 13, 1990 rain event in both the Willow and Bowron watersheds. These included bridges on Grizzly Bear Creek, Thursday Creek, and George Creek. Also, the 1990 WSC streamflow records for the Willow River state that the peak flow value was "estimated." This indicates that there was a failure in the streamflow recording system and that a true measurement is not available. It is thus possible that the 1990 flood in the Willow River was actually larger than estimated, and that it had a return period resembling that in the Bowron.

The flood of record in the Bowron River occurred on June 13, 1990 and well exceeded any previous floods on record, and was assessed as having a return period greater than 50 years (Figure 3). This type of flooding event has the potential to cause significant streambank erosion that may result in a wider stream channel.

Annual nival flows The adjustment of stream-channel form is affected by both the magnitude and the duration of flood flows (Knighton 1984). In the past 42 years, the important flood events in the Bowron and Willow watersheds have all been snowmelt- produced or snowmelt-related. It may be useful to consider the total nival flows as those possibly doing most of the geomorphic work of the stream channel and to consider them as separate from the unusual events caused by other runoff processes. The analysis of the annual total nival flow may provide additional information, relative to changes in channel width, at least for snowmelt-dominated watersheds.

For north-central British Columbia the volume of the nival flow is estimated by computing the total discharge during April, May, June, and July, the months that include virtually all of the nival melt. Figure 10 presents the long-term trends of annual nival flows for three large snowmelt-dominated watersheds located in the vicinity of the study area. For the Bowron and McGregor rivers there is a clear trend towards decreasing nival flows during the "early period" of this study (i.e., 1965–1984) and consequently a possible reduction in the channel-forming geomorphic work. The Willow River presents a similar trend, although not as substantial as the other two water-

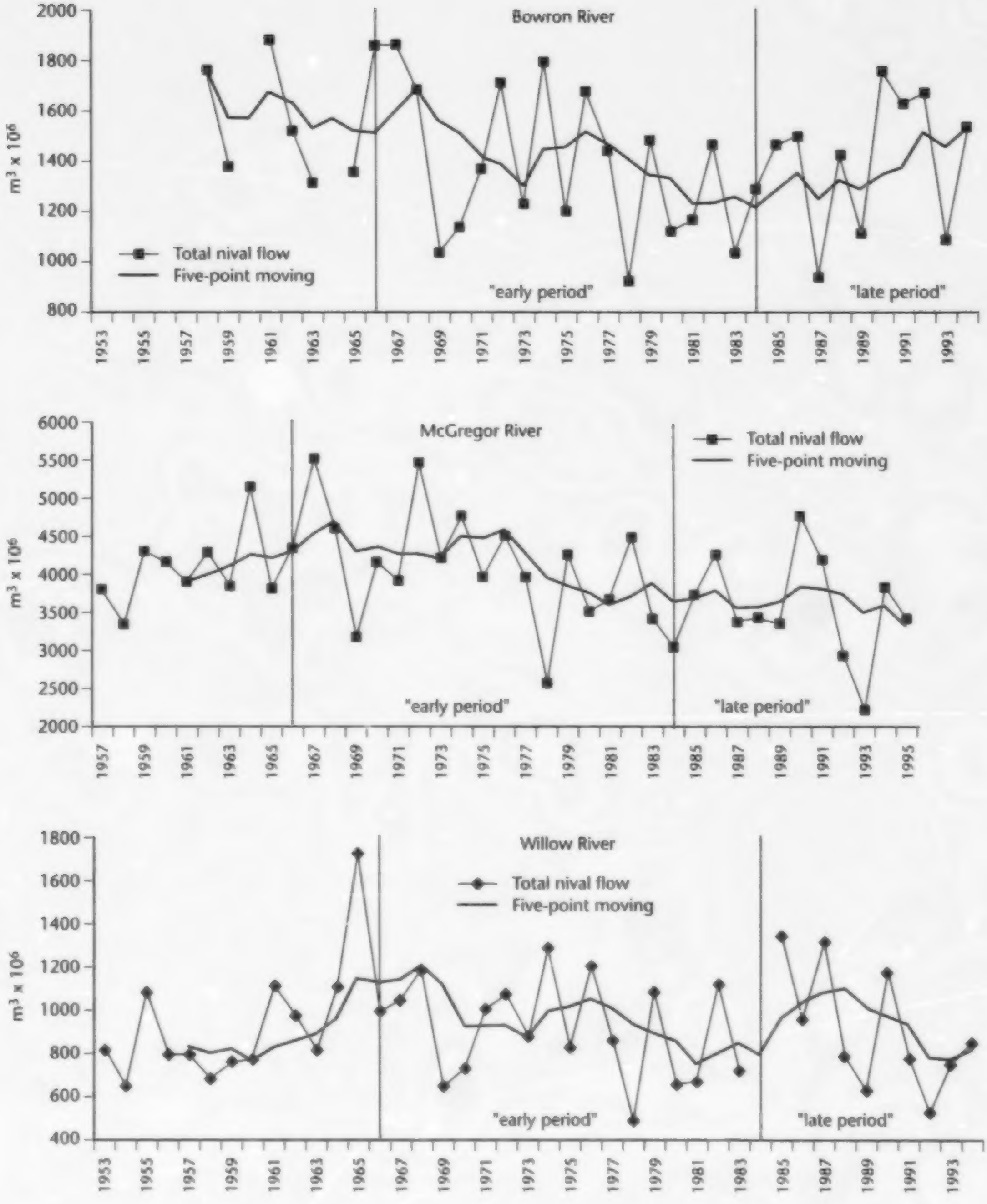

FIGURE 10 *Annual nival flood volumes for the Bowron, McGregor, and Willow rivers.*

sheds. If you accept that this "early period" was one of quiet activity, from the point of view of fluvial work, then the observation that stream channels decreased in width during this period is intuitively reasonable.

These observations of a reduction in nival flows from 1966 to 1984 correspond quite well to the historical snowpack data collected at the Barkerville snow course, which is located near the watershed divide between the upper Willow and Bowron rivers (Figure 11).

Regression Analysis

The relationship between the amount of harvesting and the change in channel width during the "early period" is presented in Figure 12. This "early period" relationship suggests that the width of the stream channel decreases as the amount of forest harvesting increases in a watershed. We believe that this interpretation is nonsensical and not a true representation of cause and

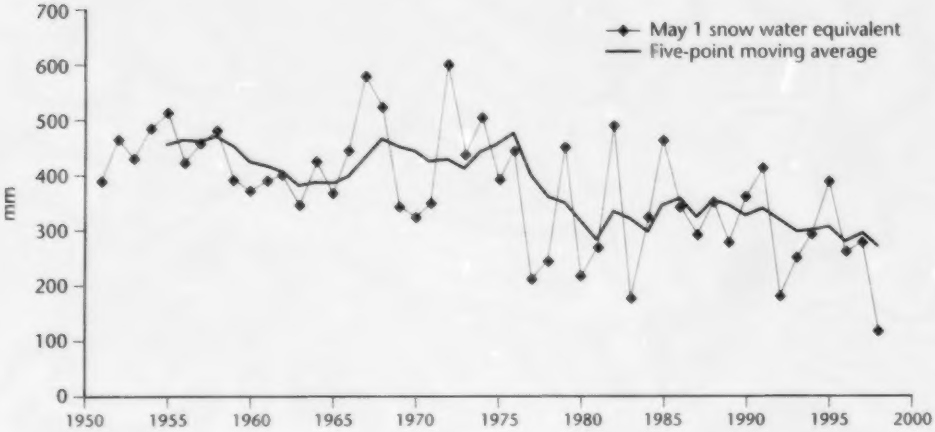

FIGURE 11 *May 1 snow water equivalents at the Barkerville snow course.*

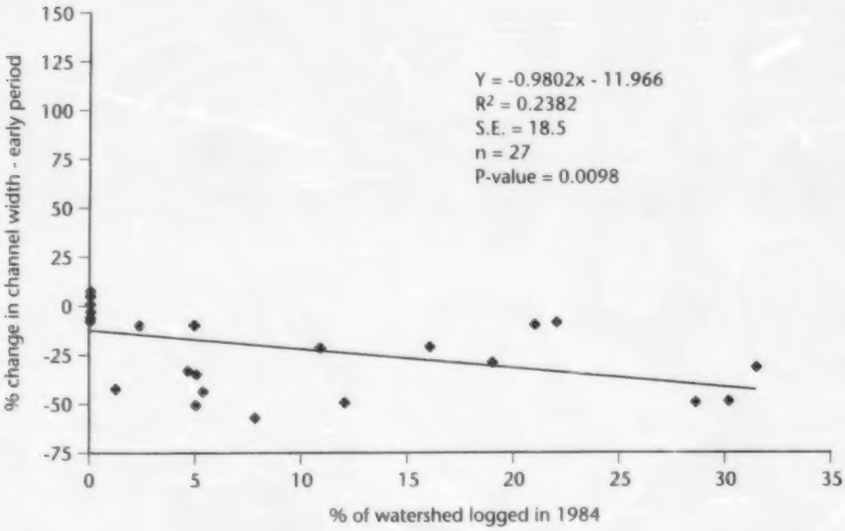

FIGURE 12 *Linear regression of the change in channel width during the "early period" and the percentage of the watershed harvested at the end of the "early period."*

effect. Based on our understanding of watershed processes, we cannot envision a situation where an increase in the amount of harvesting within a watershed would directly cause a decrease in the stream-channel width. Other processes, such as climate and the particular characteristics of the stream channel are probably controlling changes in channel width, rather than the amount of harvesting, and the significant relationship is just coincidental. We believe that this result is a Type II error; that is, the null hypothesis is really true and it is rejected by the sample.

During the "late period," the maximum amount of forest harvesting in the study watersheds reached 42%. During this time, the amount of harvesting increased in all of the study watersheds. Forest harvesting in Dominion and H1 watersheds remained below 1% (Table 4). The relationship between the amount of forest harvesting and the change in channel width during the "late period" is presented in Figure 13. The linear regression is not statistically significant. This suggests that there is no clear relationship between the amount of forest harvesting in the study watersheds and the change in stream-channel width for the interval between 0 and 42% of the watershed harvested. This relationship does not suggest that there was no change in channel width during the time period studied, but rather that this change was not directly caused by the amount of forest harvesting in the watershed. Indeed we did document changes in channel width, for both the "early" and "late" periods. During the "early period" most of the stream channels decreased in width, which corresponded to a period of relative quiescence in terms of fluvial work. This is in contrast to the "late period," which experienced a large flood event and an increase in channel width in many of the reaches measured.

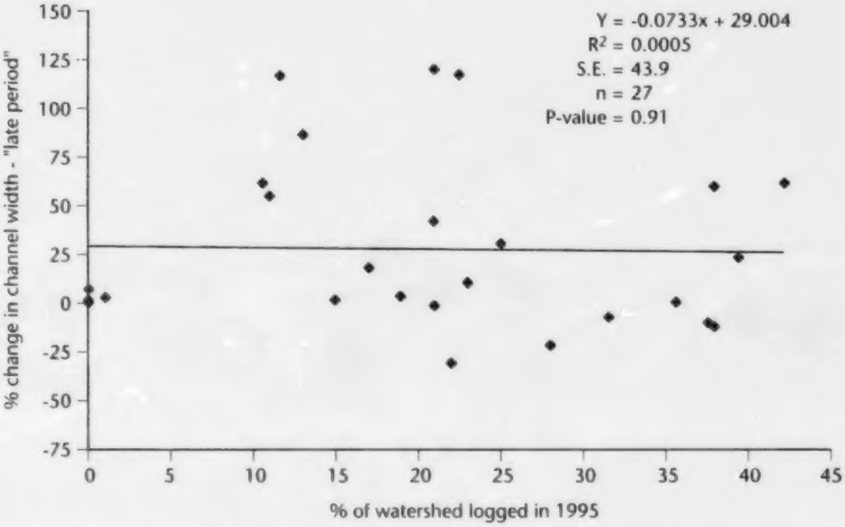

FIGURE 13 *Linear regression of the change in channel width during the "late period" and the percentage of the watershed harvested at the end of the "late period."*

In the northeastern section of the Fraser Plateau of British Columbia, post-logging stream-channel changes are often subtle. The watersheds of this interior region are not like the coastal watersheds of British Columbia and southeast Alaska, where forest harvesting can cause substantial increases in mass movements—most often initiated by road construction and forest removal—and dramatically change sediment budgets of the fluvial system (Roberts and Church 1986; Grant and Wolff 1992; Hartman et al. 1996). These increases in the supply of coarse sediment to the stream network can dramatically change stream morphology (Montgomery et al. 1995; Hartman et al. 1996; Wood-Smith and Buffington 1996; Hogan et al. 1998; Hogan 1989). Over a period of almost two decades (i.e., the "early period"), changes to the channel width of tributary streams of the Bowron and Willow River watersheds were generally modest.

The aim of this project was to investigate whether there was a direct relationship between the level of harvest in a small to medium-sized watershed of the central interior and changes in stream-channel widths. In our study, increases in channel width, observed during the "late period," were not significantly related to the level of forest harvesting within the watershed. The maximum amount of forest harvesting in the study watersheds was 42%. Stream-channel width may respond to higher levels of forest harvesting, but this could not be determined from this study. It is assumed in this study that a significant increase in channel width is an indicator of detrimental impacts on fish and their habitat. This is caused by dramatically changing the coarse sediment supply and in-stream distribution of sediment.

The changes in stream width observed in our study appear to have been driven by the natural variations in regional climate and an extreme runoff event, rather than the amount of forest harvesting within the watershed. During the "early period," extending from the mid 1960s to the mid 1980s, the annual nival flows appear to decrease, resulting in a probable reduction in the amount of fluvial activity. This resulted in the narrowing of most of the stream-channel reaches in the study. During the "late period," extending from the early 1980s to the mid 1990s, about one-half of the study reaches experienced substantial channel widening, while the other half experienced very little change. It is likely that most of the observed channel widening occurred as a result of the very large flood event of June 13, 1990. This channel widening appeared to be independent of the amount of forest harvesting in the watershed.

The observed channel widening during the "late period" could not be attributed to increases in the supply of coarse sediment from upland sources, such as mass wasting. The sediment source survey indicated that the upland supply of coarse sediment remained relatively constant, for all reaches, over the time span of the study.

This study was set up to investigate the effects of the "level of harvest" in a watershed on the changes in stream-channel width. The study watersheds were selected to provide a fairly even distribution of samples, representing a spectrum of levels of harvest that are typical for watersheds of this size in the vicinity of Prince George. This study could not establish a clear relationship between these two variables. However, during the course of this investigation we noticed that other harvesting-related variables could possibly serve to explain the variations observed to changes in stream-channel width. One of the variables that appears to be potentially important is the extent of harvesting along the edge of the stream channel (i.e., riparian harvesting). Many of the stream reaches that experienced channel widening were also logged to the edge. The opposite was also true; that is, several reaches experienced channel widening despite the lack of riparian logging. We think that the extent of riparian harvest is an important variable, and, associated with stream power and the level of harvest in the watershed, may better describe the variability in changes to stream-channel width observed in this study. This is certainly an important management issue and could be the subject of an interesting and worthwhile investigation. The paper presented here by Millar (2001) provides some very interesting data to support the idea that the extent of riparian harvest can have a significant impact on channel widening.

The authors are personally familiar with several other stream channels, in proximity to the study streams, that experienced similar widening during the "late period" (mostly caused by the June 1990 flood). These include Stone Creek, Narrow Creek, tributaries of upper Indian Point Creek, and tributaries of Haggen Creek, where the amount of harvesting varies from less than 1% to about 45% (Beaudry and DeLong 1996; Berris 1997; British Columbia Forest Service 1996; Soto et al. 1997). These informal observations support the findings of this study, which concludes that there is a poor relationship between the level of harvest in a watershed and channel widening during the "late period." These observations also suggest that the study watersheds are representative of other watersheds in the area.

Recognizing the often subtle nature of stream-channel change in this region suggests that future similar work be performed using a set of watersheds better matched for channel gradient and size. However, in a retrospective study, it is often very difficult to choose experimental units (e.g., watersheds) for testing the effects of a specific variable (e.g., extent of forest harvest), while maintaining other variables constant, such as size of watershed, extent of riparian logging, or stream power. The uncontrolled nature of a retrospective study of this kind means that the investigator must work with the "experimental units" and "treatments" available at the time of the study. We focused our study on watersheds ranging in size between 30 and 75 km^2 because we think that these are the most sensitive to forest-harvesting operations. Unfortunately, in the Fraser Plateau, the streams that drain watersheds of this size are often too small for adequate air-photo resolution. All of these factors impose potentially severe limitations on the power of the statistical analysis.

ACKNOWLEDGEMENTS

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Sediment Budgets in the Nelson Forest Region

PETER JORDAN

ABSTRACT

We have ongoing sediment-budget studies in two parts of the Kootenays: at Redfish-Laird creeks in the West Arm Demonstration Forest, and at Gold Creek, one of the community watersheds of the City of Cranbrook. In addition, a number of watersheds have had monitoring programs that provide some sediment-budget information for 1 or more years.

The Redfish-Laird study began in 1993. Results show that April–September sediment yields for each year in Redfish Creek, which is developed with roads and logging, ranged from 25% greater than to double the yields for Laird Creek, the control. Most of the difference is probably attributable to erosion from roads, and to a lesser extent, to road-related landslides that occurred before the study began. Road-maintenance activities can contribute significantly to sediment production. Contributions of sediment from cutblocks were insignificant.

The study in Gold Creek, which began in 1998, has so far shown much lower development-related sediment inputs to the creeks than in Redfish Creek. This is apparently due to a fundamental difference between the two areas in runoff generation mechanism. At Gold Creek, most of the snowmelt runoff from upland areas appears to enter fractured bedrock, and reach the creek through groundwater flow. This results in a low connectivity between sources of eroded sediment and the creek. In contrast, the hydrograph of Redfish Creek is dominated by surface runoff, and the sediment deliverability from roads to the creek is higher.

In 1997, we monitored suspended sediment production on 11 creeks used for community and domestic water supply. Watersheds underlain by granitic rocks tended to have the lowest average sediment yield; otherwise, there was little apparent relation between sediment yield and bedrock geology or extent of development. In general, sediment yield from most creeks used for water supply was quite low compared to typical yields elsewhere in British Columbia.

A sampling strategy of daily manual sampling during the spring freshet, and less frequent sampling for the rest of the year, has been found effective both for measuring total sediment yield and for monitoring water quality. Recording turbidity meters provide additional useful information.

INTRODUCTION

For about the last 20 years, the British Columbia Ministry of Forests has been sampling suspended sediment in a number of watersheds that are used for community and domestic water supply in the Nelson Forest Region. This monitoring was done mostly on a piecemeal basis, due to local concerns about the effect of forest development on water quality. In the early 1990s, we began more systematic research into the sediment budgets of community and domestic-use watersheds.

A sediment budget is a quantification of the sources of sediment, changes in sediment storage in the stream channel, and sediment discharge at the outlet of the watershed or channel segment of interest. For practical purposes, sediment can be divided into two categories: fine (fine sand, silt, and clay), and coarse (coarse sand and gravel). Fine sediment is carried in suspension in the water, and is deposited only when streamflow velocity is low, such as in low-gradient reaches, back channels, and lakes. Fine sediment causes turbidity (cloudiness) in the water, and is of concern for water quality as well as for fish habitat. Coarse sediment is carried as bedload on the stream bottom, and is of interest for fish habitat and for the flood behaviour and stability of stream channels. Often it moves only during the highest flows of the stream, and is stored for long periods of time in channel bars and banks.

In our sediment-budget studies, we have concentrated on suspended sediment. This is because suspended sediment and turbidity are of the most interest for water quality, and also because suspended sediment can be easily sampled, while bedload movement is extremely difficult and expensive to sample.

The main objectives of our studies are to:

- identify natural and development-related sources of sediment in typical watersheds that are used for community water supply;
- investigate the effect of road construction, maintenance, and deactivation, and of different silvicultural systems, on sediment production;
- investigate the physical processes by which sediment is delivered to the channel system, stored in channels, and discharged at the stream outlet; and
- investigate precipitation and snowmelt events that are significant in sediment production.

In a review of suspended sediment data collected by the Water Survey of Canada (WSC), Church et al. (1989) noted that sediment yields in British Columbia rivers tend to increase downstream, with large rivers having high sediment yields, and small, upland tributaries having relatively low yields, unless they are glacier-fed or subject to mass movement or other disturbance. This reflects the fact that the most significant sediment sources for many rivers are the extensive glacial deposits that are stored in the river valleys, and are still being eroded by the main river channels, while such deposits are typically thin or absent in upland areas. Also, in the data they summarize, it is notable that small creeks in the Kootenay region that are used for community water supply have the lowest sediment yields of all the streams sampled, with average annual yields of typically 2–10 t/km^2/y, com-

Apparently the use of surface water for community water supply in the region is not an accident; these streams were deliberately chosen for their low sediment concentration and high water quality.

REDFISH AND LAIRD CREEKS: TOTAL, SEASONAL, SUSPENDED-SEDIMENT YIELD

The sediment-budget study on Redfish and Laird creeks began in 1993, as part of the West Arm Demonstration Forest project near Nelson. The design and methodology of the study, and the results of the first 4 years, are given by Jordan and Commandeur (1998). The basic design is a paired watershed study, with Redfish Creek having roads and ongoing forest harvesting, while Laird Creek, which is undeveloped, is a control. The two watersheds are adjacent, and have very similar topography and soils. Their areas are 26 and 15 km^2, respectively.

Streamflow is measured continuously near the mouths of Redfish and Laird creeks by the WSC. A turbidity meter is installed at each stream-gauging station, and a local resident collects water samples on each creek—daily during the snowmelt period and once-to-twice weekly at other times. Also, within the Redfish Creek watershed, a number of additional measurement and observation sites are maintained. A tributary stream of 1.15 km^2 has two stations—one at the mouth and one above the development area—each with a v-notch weir, water-level recorder, and turbidity meter. These serve as an upstream-downstream pair, with the undeveloped upstream part of the watershed acting as a control. There are several other weirs on other tributaries, serving mainly as sediment traps, as well as simple sediment traps below culverts at several locations. A network of climate stations and snow courses, and a snow pillow, provide supporting data. Figure 1 shows the main instrument stations in the Redfish Creek watershed, and Figure 5 is a photograph of the upper Redfish Creek watershed.

The total sediment yield for a year, or for any other period of interest, can be calculated simply from the daily discharge and the sediment concentration of the daily sample. However, it relies on the assumption that the daily sample is representative of the average concentration for the entire day. Because our continuous turbidity data indicate considerable diurnal variation in turbidity, this assumption may be a major source of error. Theoretically, the continuous turbidity data should enable more precise calculation of suspended sediment yield, if an accurate rating curve of sediment concentration vs. turbidity can be constructed. However, there is considerable scatter in this rating curve. Also, we have found that turbidity meters often give erroneously high values during high discharge in the creeks, which are very steep and turbulent, probably due to bubbles and debris in the water. The use of turbidity meters for calculating sediment yields, and some operational problems of using these instruments, is discussed by Jordan and Commandeur (1998) and Jordan (1996).

For the purpose of this paper, sediment yields based on the daily sediment sample are used. Recently, we have been using automatic pump samplers to collect up to four samples per day for each creek to get a more representative sample of daily sediment concentration; however, the results were not available at the time of writing this paper. The continuous turbidity data are used

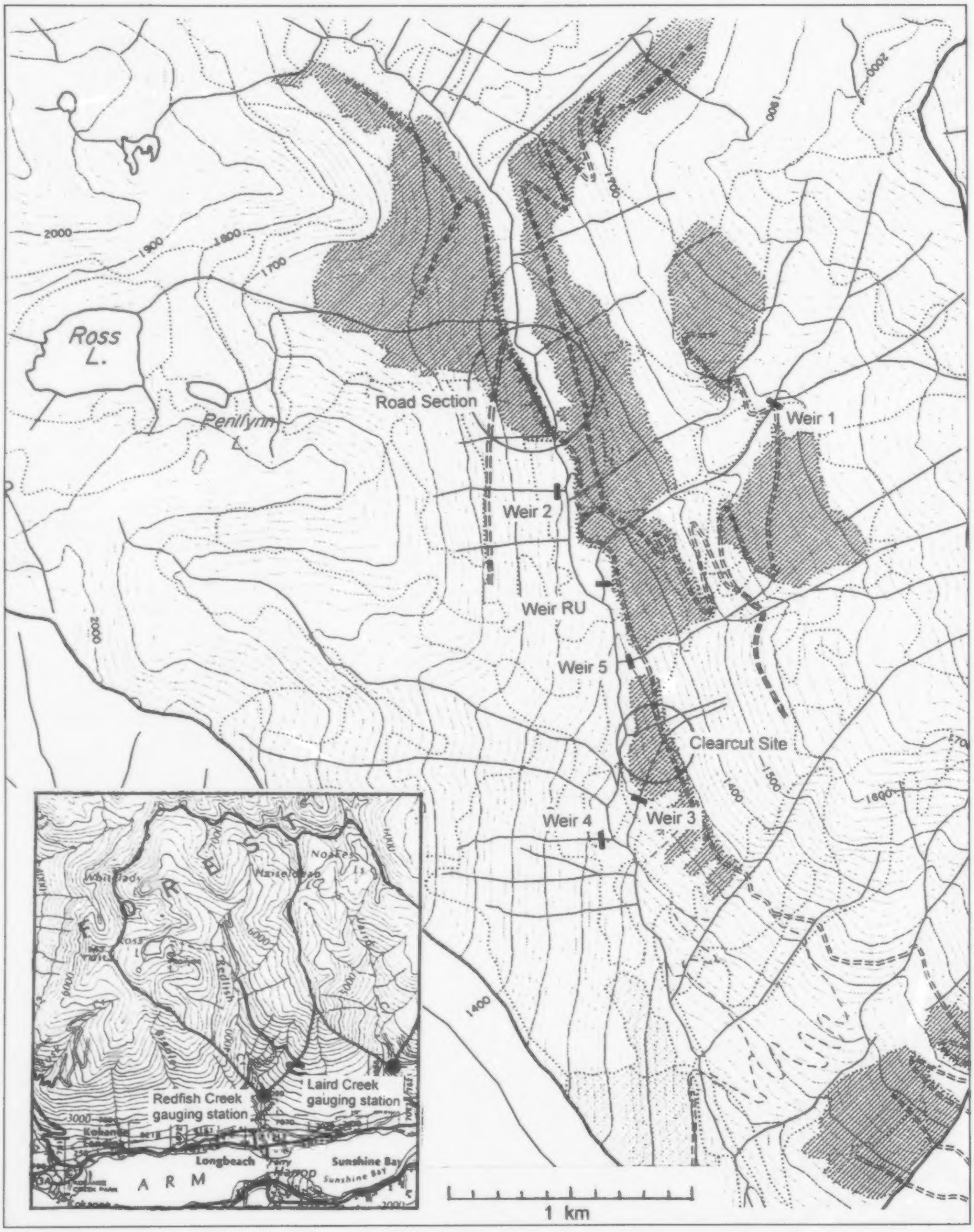

FIGURE 1 *Map showing Redfish and Laird creek watersheds, and location of field installations at Redfish Creek. Inset map scale is approximately 1:140 000. Dark grey stippled areas are clearcuts. (Figure from Jordan and Commandeur 1998.)*

mainly to document the sediment yield during summer rainstorms, at which time discharge is lower and the turbidity meters operate quite reliably.

Sediment data are collected only during the months of April through October, although streamflow is measured during the winter as well. In this region, almost all (at least 90%) of the sediment yield occurs during the spring and early summer. Sediment yield during the winter low-water season is negligible, except during very rare winter rain-on-snow events (one such event occurred in November 1999).

The April–September streamflow and sediment yields for Redfish and Laird creeks are summarized in Table 1. These essentially represent the annual sediment yields. Data for 1997–1999 are preliminary, and are subject to revision of streamflow data. (We believe that streamflow for Laird Creek may have been underestimated for these years, due to some problems with the rating curves used by the WSC.) The results show a consistent trend of higher unit-area sediment yield on Redfish Creek. Although these results alone do not definitively show that the higher sediment yield on Redfish Creek is due to forest development, additional data from specific sediment sources strongly suggest that this is the case.

The data for the upstream and downstream weirs on the tributary creek provide additional information supporting the conclusion that development-related sediment sources are significant. The lower weir includes in its watershed parts of several old cutblocks, about 2.3 km of road (including four switchbacks), and the scars of two landslides from about 1990. The lower weir shows consistently higher sediment yield than the upper control weir (data from Jordan and Commandeur 1998). Figure 2 shows the spring-season water level and turbidity records at the two weirs, and clearly shows higher turbidity at the lower weir during the main snowmelt event.

Table 2 summarizes the results of sediment source observations during the first 4 years of the study, based on the data reported by Jordan. Observations of erosion in cutblocks, including one detailed survey of erosion in a freshly harvested and burned block, show that sediment from timber-harvesting operations and for previously harvested cutblocks is negligible. However, erosion from road surfaces is a very significant source of sediment. Road-erosion surveys showed typical values of erosion at the source in the order of 20–200 t from about 19 km of road. However, it is difficult to

TABLE 1 *Summary of stream discharge and April–September suspended sediment yield for Redfish and Laird creeks*

	1993	1994	1995	1996	1997	1998	1999
Redfish Creek: total April–Sept. runoff (mm)	600	695	703	1075	1250	820	1077
Redfish Creek: peak daily discharge (m^3/s)	5.28	4.79	5.45	6.51	8.94	6.59	7.14
Sediment yield: April–Sept. (t/km^2)							
Redfish Creek	9	2	5	10	11	6	10
Laird Creek	4	1	4	8	5	3	3

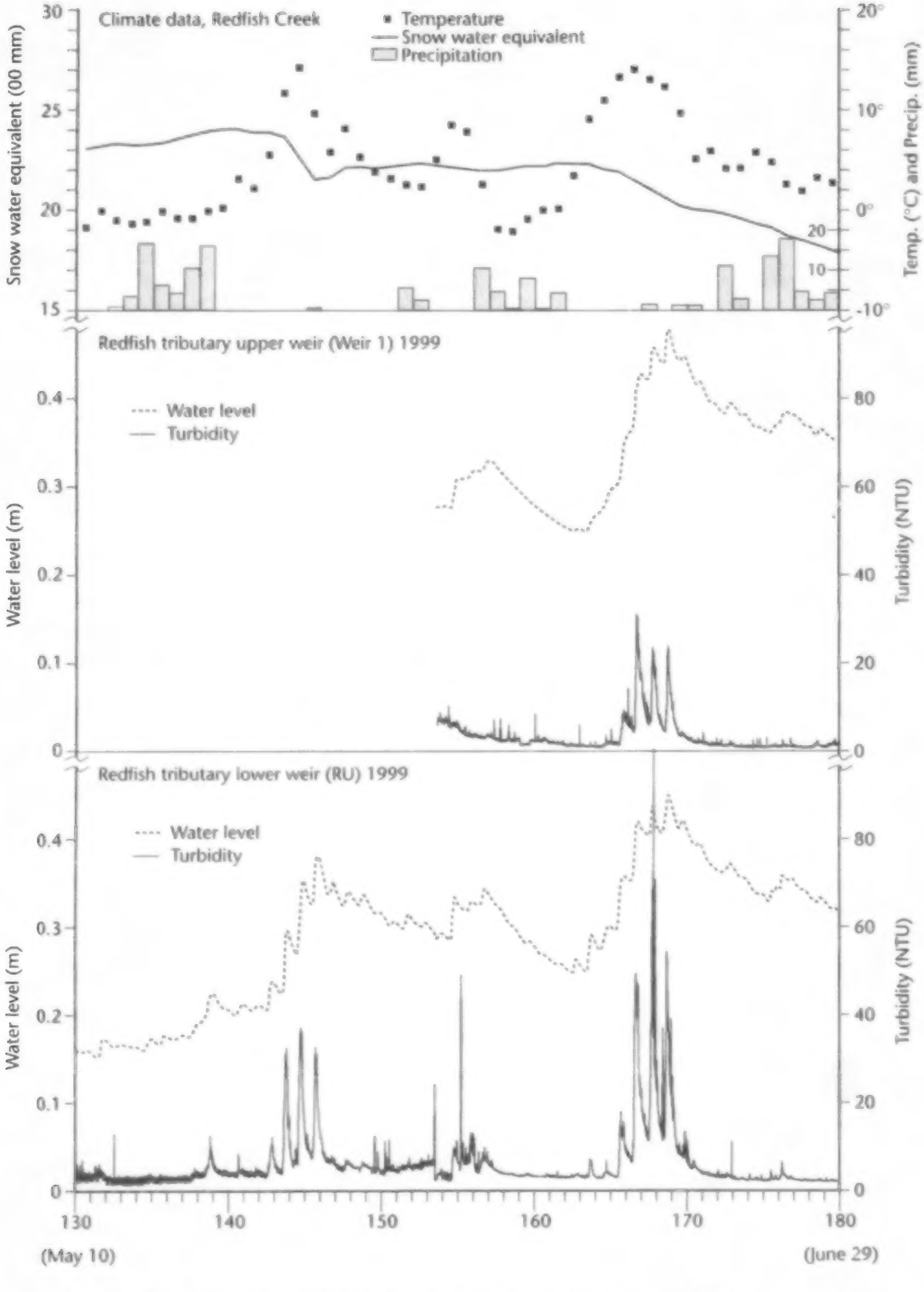

FIGURE 2 *Redfish tributary water level, turbidity, and climate data for spring 1999. Snow pillow data and temperature from station at 2100 m; precipitation from rain gauge at 1300 m. X axis is Julian day. Data are preliminary. Water level is to an arbitrary datum. Turbidity has not been corrected for drift of the OBS meter zero.*

TABLE 2 *Development-related sediment sources, Redfish Creek sediment-budget study*[a]

Source and estimated typical annual yields	Eroded at source	Delivered to creek
Cutblocks		
• Recent (last 10 y) - approx. 30 ha x 1 t/ha	30 t	< 1 t
• Old - approx 230 ha x ?	?	< 1 t
Roads	20–200 t	5–50 t
Estimates range from:		
• Typical rates are 0.1–20 m^3/y (0.16–32 t/y)		
• Length of road 19 km		
In 1993, approx. 133 t eroded from 0.5 km length, estimated delivery 10–50 t		
Episodic events (landslides)		25 t/y
Average annual delivery:		
• five landslides, volume approx. 4000 m^3 , delivered 1000 m^3 or 1600 t, of which approx. 500 t is suspended		
Time period of 20 years (a risk, not an actual annual delivery)		

[a] Typical annual suspended sediment yield for Redfish Creek is 100–200 t.

estimate the proportion of the sediment that is delivered to stream channels. Also, road erosion varies greatly from year to year and from location to location; often, most of the road-related sediment is produced from a few short sections of road that experienced failure of the drainage system, such as a blocked culvert or ditch. In 1993, a major erosion event related to a blocked culvert produced at least 100 t of sediment in a few days, and may have amounted to up to one-quarter of the annual suspended sediment yield that year (Figure 6).

Landslides are an episodic process that occurs relatively rarely in the British Columbia interior compared with wetter regions such as the coast, but if a large landslide does occur it can dominate the sediment yield for that year. The presence of roads in steep terrain greatly increases the likelihood of landslides. No significant landslides have occurred in Redfish or Laird creeks during the course of the study.

Although the results clearly show that Redfish Creek has a higher sediment yield than Laird Creek, and the difference is probably due largely to forest roads, it is not clear that the impact on water quality is significant. A generally accepted standard for turbidity in domestic watersheds is 1 NTU for water in a distribution system, and 5 NTU for creek water at the source. Table 3 shows the number of days in each year for which the daily water sample exceeds this threshold. It also shows the number of days for which the maximum reading of the turbidity meter exceeded 20 NTU. This higher value was chosen because high turbidity peaks are often of very short duration, and brief transient peaks often occur on days when the average turbidity is low. By both measures, Redfish Creek shows a higher incidence of turbid water in most years. However, on both creeks, the number of high-turbidity days is very small.

TABLE 3 *Days for which turbidity exceeds water-quality criteria*[a]

	Turbidity meter		Sediment samples	
	Redfish Creek	Laird Creek	Redfish Creek	Laird Creek
1993			6	4
1994			0	0
1995	10	5	5	2
1996	6	6	1	2
1997	17	5	5	3
1998	2	5	3	1
1999			4	2

[a] Daily sediment samples = 5 NTU. Maximum, daily, 15-min average of the turbidity meter = 20 NTU.

SEDIMENT PRODUCTION FROM SUMMER RAINSTORMS

Summer rainstorms, which are sometimes short-duration thundershowers, produce significant rises in the stream hydrograph; however, peak discharges are rarely as high as average discharge during the spring snowmelt period. Considerable amounts of road erosion are sometimes observed during these events. Although high stream turbidity sometimes occurs, the sediment yield during these events (which is sediment concentration x stream discharge) is usually lower than would be expected. In our experience of observing of erosion processes, what typically happens is that much of the sediment eroded from roads during summer rainstorms is carried only a short distance, and is stored in ditches, and in gullies or hollows below culverts, as the water infiltrates. In the spring, the connectivity between the road drainage system and the stream channels is much higher, as continuous overland flow occurs in many ditches, and in swales and gullies in the forest. During the first significant rise in the hydrograph in the spring, much higher turbidity is usually observed in Redfish Creek than in Laird Creek. This may be caused by stored sediment that had eroded the previous summer being entrained and reaching the creek.

Figure 3 shows the water-level and turbidity records of Redfish and Laird creeks, and the two weirs on the tributary stream, during two rainstorms in August 1999. Redfish Creek has higher turbidity than Laird Creek during the first, August 8 (day 220), storm. On the tributary, the lower weir shows higher turbidity than the upper weir during both storms, especially the first one. About 2 weeks earlier, the roads in the watershed had been graded, and work included cleaning the ditches with a grader in many places. The first rainstorm resulted in extensive erosion and sediment production from the ditch line. Our general observations during the course of the study is that frequent grading of the roads and ditches is a major cause of sediment production, as compared to roads that are infrequently graded and ditch lines that are protected by vegetation growth. The fact that the first rainstorm following the grading caused an unusually high influx of sediment to the creek, and the second one did not, supports the conclusion that the road grading was a major cause of erosion. Figures 7 and 8 show road grading and some of its effects on sediment production from ditches.

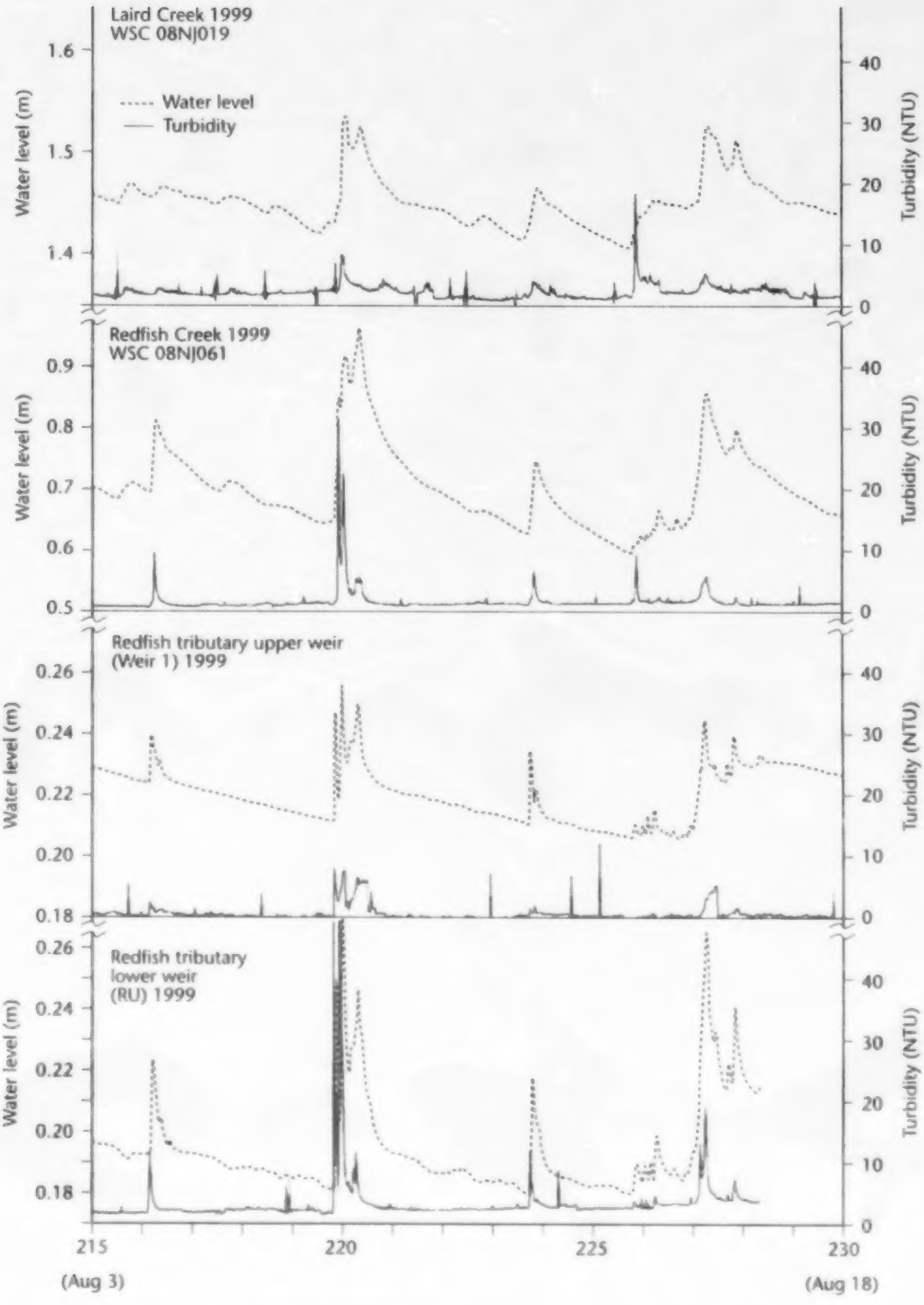

FIGURE 3 *Water level and turbidity data for summer rainstorms, Laird and Redfish Creeks and Redfish tributary. Data are preliminary. Water level is to an arbitrary datum. Turbidity has not been corrected for drift of the OBS meter zero.*

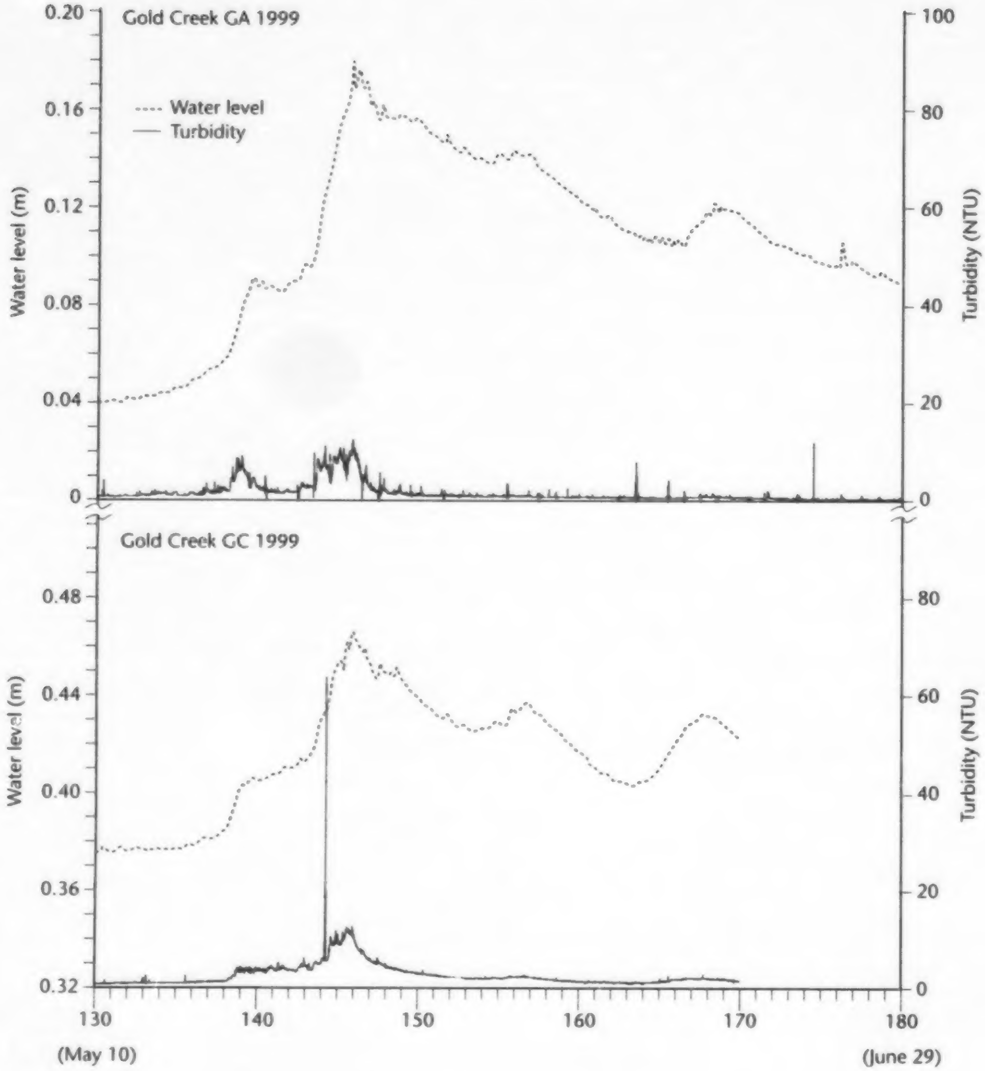

FIGURE 4 *Water level and turbidity for Gold Creek tributaries, for spring 1999. X axis is Julian day, for the same period as Figure 2. Data are preliminary. Water level is to an arbitrary datum. Turbidity has not been corrected for drift of the OBS meter zero.*

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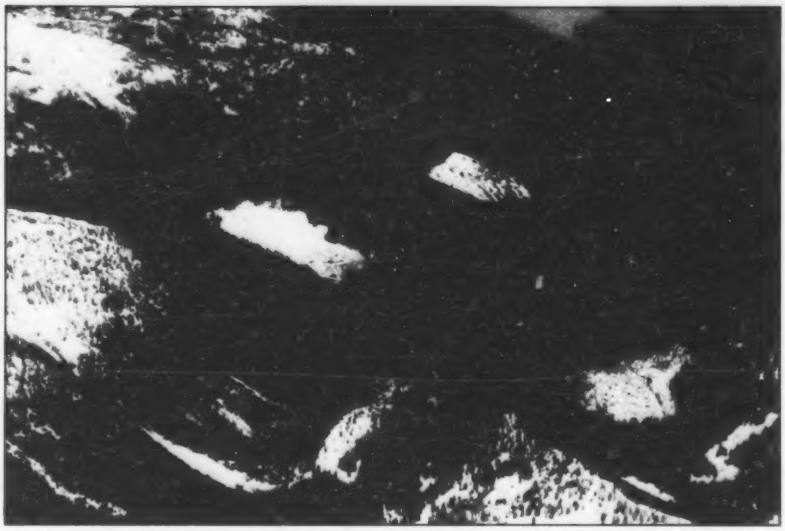

FIGURE 5 *Overview of the upper Redfish Creek watershed during snowmelt. The instrumented tributary is in the upper right part of the picture.*

FIGURE 6 *An extreme road-surface erosion event in May 1993, caused by a blocked culvert at the top of a hill, and a lack of water bars.*

FIGURE 7 *Example of ditch erosion following grading of ditches, August 1999. A buried culvert is by the stake in the foreground.*

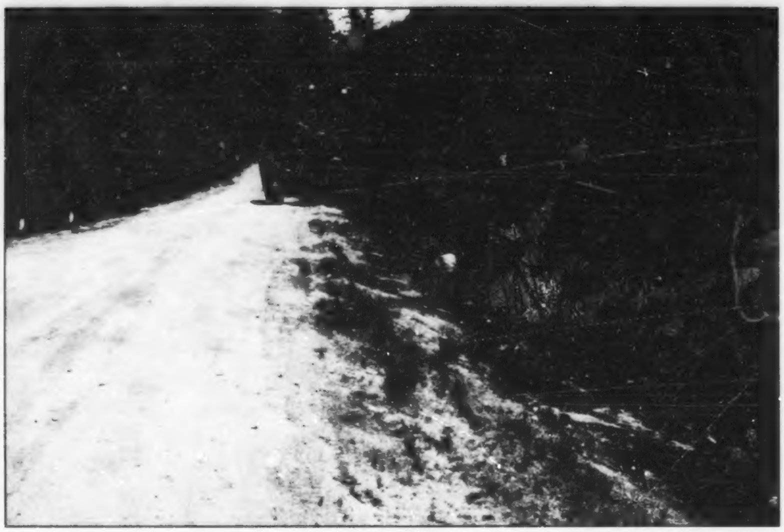

FIGURE 8 *Grading the road ditches, Redfish Creek, July 1999. The fine sandy soil in this part of the watershed causes a high potential for road-surface erosion.*

GOLD CREEK: OBSERVATIONS ON THE ROLE OF GEOLOGY ON RUNOFF PROCESSES

The sediment-budget study on Gold Creek, one of the community watersheds supplying the City of Cranbrook, began in 1998. This area is drier than the Redfish Creek area, and the topography is less rugged. Also, the geology is different: the Gold Creek area is underlain by fractured sedimentary rocks of the Purcell group, while Redfish Creek is underlain by granite of the Nelson batholith.

For this study, three adjacent small tributaries of Gold Creek were selected, with very similar elevation ranges and topography:

- GA, 2.6 km^2, had extensive new development in 1998 and 1999, including about 3.2 km of new road, and four new cutblocks totalling about 40 ha, as well as some older roads and logging from about 1992;
- GB, 3.4 km^2, has some roads and logging from about 1992, but not as extensive development as GA; and
- GC, 2.6 km^2, is an undeveloped control.

Each watershed is equipped with a water recorder, turbidity meter, and an automatic pump sampler that takes daily water samples. Rectangular weirs were installed on GA and GB, while GC, which is inaccessible by vehicle, has a natural gauging section. GB is somewhat unlike the other two watersheds in that its channel was apparently disturbed by a debris torrent in 1997, and as a result the channel is unstable and transports an unusual amount of sediment from channel bank sources. However, GA and GC make a reasonably well-matched pair for examining the effects of development. Figure 9 is an overview of watersheds GA and GB.

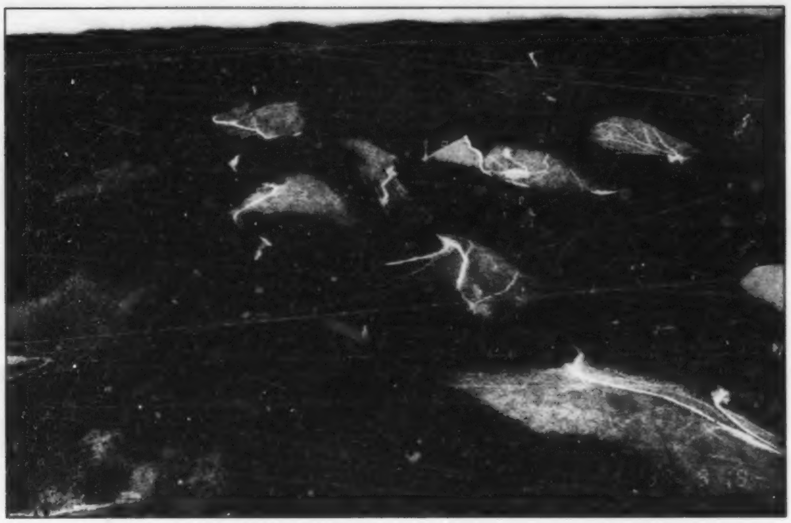

FIGURE 9 *Overview of the Gold Creek tributary watersheds, September 1998. GA is in the centre of the photo. Three additional cutblocks were logged along the upper road in 1998 and 1999. GB is on the right.*

Unlike Redfish and Laird creeks, the data so far show that the effect of development on the GA sediment yield has been minimal. Figure 4 shows the water level and turbidity for GA and GC for the snowmelt season of 2000. There is no significant difference between the two creeks, except for a slightly higher turbidity on the initial early-season rise of the hydrograph on GA. Turbidity during the spring freshet is much lower than on the Redfish Creek tributary.

On examining the new roads in the GA watershed shortly after snowmelt, it was noticed that road and ditch-line erosion, although present at some locations, were much less extensive than at Redfish Creek. It appeared from the lack of continuous sediment tracks in the ditches that the runoff infiltrated into the ditches rather than running to the nearest culvert or creek. Also, it appeared that most water flowing from culverts infiltrated into the ground within a short distance, rather than forming continuous pathways of overland flow as at Redfish Creek. This difference appears to be due to differing bedrock geology. In the Gold Creek tributaries, bedrock lies at a very shallow depth over most of the watersheds, typically less than 1 m, and tree roots usually reach bedrock, so there is a hydrologic pathway for water to infiltrate into the soil and to enter the bedrock. The bedrock is quite fractured, so it appears that most runoff infiltrates deep groundwater storage in the bedrock. Figure 10 shows a typical section of 1-year-old road, and the lack of surface erosion, compared to Redfish Creek.

Comparing the hydrographs for the upland tributaries of Redfish Creek and Gold Creek for the same period (Figures 3 and 4), it is obvious that, at Redfish Creek, there is a strong diurnal cycle of streamflow, while at Gold Creek, the diurnal cycle is almost completely lacking. This is consistent with a runoff mechanism dominated by overland flow and rapid subsurface flow on Redfish Creek, and one dominated by deep groundwater flow on Gold Creek. (On the main 95 km^2 Gold Creek, where we also have a water level recorder, a diurnal cycle is present, although not as prominent as at Redfish

FIGURE 10 *Two-year-old road and logging in GA, June 2000. Note the lack of evidence of overland flow or surface erosion. Most snowmelt runoff infiltrates into fractured bedrock, which is exposed in the ditch.*

Creek. This suggests that there are saturated areas of groundwater outflow, or areas that generate overland flow elsewhere in the watershed, probably in the valley bottom.)

In the context of sediment budgets, the significance of the difference in runoff generation mechanisms is that in the impermeable, surface-runoff–dominated Redfish Creek, there is high connectivity between development-related sources of erosion, such as roads, and the creek, resulting in high sediment yields. In the more permeable, groundwater-dominated Gold Creek, connectivity is much lower, so there is a much lower sediment yield from development-related sources.

DISCUSSION AND CONCLUSIONS

The results of sediment-budget studies on Redfish and Laird creeks clearly show that development-related sediment sources can increase the sediment yield of watersheds. However, in this study area, it is not clear that the increase is significant, in terms of decreased water quality. Erosion from road surfaces and ditches appears to be the single most important source of development-related sediment.

The data from Gold Creek show that connectivity of runoff from erosion sites to streams is a critical factor in the amount of development-related sediment reaching streams, and that connectivity is controlled, at least in part, by watershed geology.

In 1997, we monitored suspended sediment yield on 11 watersheds throughout the Kootenays, representing a range of geology and a range of extent of development. The results of this study are reported by Jordan and Fanjoy (1999). The suspended sediment yields on 10 of the creeks ranged from 5 to 38 t in a year that had higher runoff than average. (The eleventh watershed was an anomaly, in that its sediment budget was dominated by a large landslide.) There was a tendency for watersheds underlain by granite to have the lowest sediment yields; otherwise, there was no consistent pattern related to geology, soils, or extent of development. The creeks in our detailed sediment-budget studies, Redfish and Laird creeks and the Gold Creek tributaries, have sediment yields that are at the low end of those typical for the region.

With respect to methodology, we have found that daily sampling during the spring runoff period provides an effective and economical means of monitoring water quality and estimating the sediment budget for streams in this region. For streams with a prominent diurnal streamflow cycle, sampling several times per day during peak-flow periods is beneficial, to better represent the variability of sediment concentration. The use of automatic pump samplers facilitates more frequent sampling. Automatic recording turbidity meters can provide useful additional data, especially for short-duration events such as rainstorms.

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Using Sediment Budgets to Test the Watershed Assessment Procedure in Southeastern British Columbia

G.S. HENDERSON AND D.A.A. TOEWS

ABSTRACT

In 1997 and 1998, the British Columbia Ministry of Forests tested the appropriateness of using the sediment-source technique described in the province's 1999 Interior Watershed Assessment Procedure (IWAP) to assess the input and output of sediment in 11 sub-watersheds in the Nelson Forest Region in southeastern British Columbia. Sediment input was estimated using the Rapid Road Erosion Technique Survey (RREST), a survey technique that estimates quantities of sediment that erode from forestry roads and are transported into the stream system. Sediment output was calculated for the same sub-watersheds by measuring suspended sediment, turbidity, and streamflow, and these measurements were used to calculate sediment yield in nine of the 11 basins. Results show that, in these watersheds, forestry roads are a relatively small part of the annual sediment budget, and that natural sediment sources dominate the sediment regime. It is unlikely that rehabilitation of forestry roads would result in significant reductions in sediment yield when measured at the outlet of the basin.

1 INTRODUCTION

How forestry roads and timber-harvesting activities affect suspended sediment and turbidity in streams is of major concern to forest managers and hydrologists in British Columbia. Identifying sediment input to streams in forested watersheds and its effect on water quality are integral components of the Interior Watershed Assessment Procedure (IWAP) for British Columbia (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). In 1997, when this study was initiated, the watershed assessment approach was based on a numerical rating scheme that included such factors as the number of stream crossings, the density of roads, the density of roads on erodible soils, and the density of roads within 100 m of a stream (B.C. Ministry of Forests and B.C. Ministry of Environment 1995). The original objective of this study was to test the surface erosion and mass-wasting indices of the IWAP using a sediment-budget approach. However, in 1999, a new watershed assessment procedure was introduced; it requires that a survey of sediment sources entering streams be conducted, and it eliminates the use of the numerically derived indices (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). As a result, the modified objective of this study was to evaluate the general validity of the sediment-source evaluation technique by comparing sediment input and output at the basin level. The sediment-source evaluation technique was also compared with the original indices, which continue to be used for planning purposes and are used by some hydrologists as risk indicators (Carver 2001).

A sediment-budget study can be undertaken at various levels of detail. We applied the method to fairly large sub-watersheds (3.6–93.8 km^2), which are typical of the assessment units in the watershed assessment procedure. The methods used and developed by Jordan and Commandeur (1998) at Redfish Creek in the West Arm Demonstration Forest, located near Nelson, B.C. were modified by Henderson (1999) so they could be applied to these larger sub-watersheds.

The essence of the sediment-budget approach is to quantify both sediment input and output in streams (Equation 1):

$$\textit{sediment input} + \textit{change in storage} = \textit{sediment yield} \quad (1)$$

It is an accounting of sediment from its origin at roads and other visible sources such as landslides and natural sediment sources, to the outlet at the mouth of a sub-watershed. Sediment input to streams from forestry activities in the southern interior of British Columbia, as elsewhere, is widely considered to originate mainly from forest roads (Packer 1967; Brownlee et al. 1988; Jordan and Commandeur 1998). Generally, the introduction of fine-grained sediment (i.e., <0.5 mm diameter) to streams from forestry roads is the range of most concern because it is easily transported downstream as suspended sediment and can affect drinking-water quality and fish habitat (Hudson and Sterling 1998; Jordan and Commandeur 1998). Suspended sediment storage for more than 1 year is often minimal in mountain streams (Church 1995) and thus can be assumed to be zero in Equation 1. Sediment concentration is measured by sampling water at the mouth of the sub-watershed and analyzing it for suspended sediment. When sediment concentration is multiplied by stream discharge, the sediment yield can be determined for the sub-watershed. The benefit of the yield measurement is that it can be checked against the input measurements.

2 STUDY AREAS: SELECTION AND DESCRIPTION

Eleven watersheds and sub-watersheds were selected to reflect a combination of drainage areas, soil texture, and amount of harvesting that are typically analyzed in the watershed assessment procedure (Figure 1).[1] Other factors important to the watershed-selection process included ease of access, the extent of proposed harvesting, and whether or not complementary water-quality programs were being operated by forest Licensees and the B.C. Ministry of Environment.

The watersheds are located in southeastern British Columbia; all are in mountainous terrain with steep slopes. The sub-watersheds are located in four watersheds (Blueberry Creek, Redfish Creek, Little Cayuse Creek, and

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[1] The term watershed is used to refer to the entire catchment area above the intake, whereas sub-watershed refers to tributary catchments within the larger watershed. This terminology is consistent with the IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999).

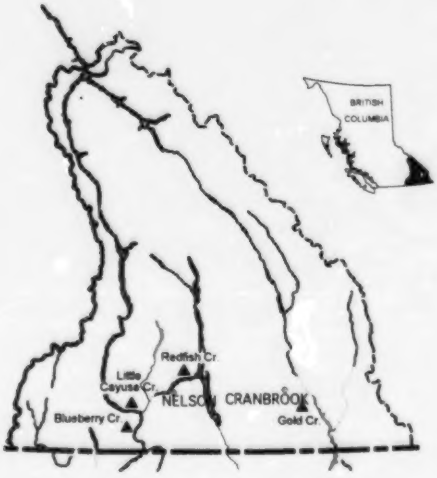

FIGURE 1 *A map showing the location of the study watersheds in the Nelson Forest Region.*

Gold Creek) used for domestic or community water supply and were usually rated with a high surface erosion or mass-wasting hazard index.[2]

Most of the watersheds have experienced a long history of logging. Typically, the ECA was over 15%; however, the ECA ranged from 0% in a residual unit in Gold Creek to over 40% in a sub-watershed in Blueberry Creek. Watersheds were classified into a coarse- , medium- , or fine-textured geology to investigate differences in sediment budget based on soil texture. Catchment area ranged from 3.6 to 93.8 km^2. Characteristics of the watersheds are shown in Table 1, including the equivalent clearcut area (ECA) and IWAP hazard indices.

3 METHODS

3.1 Sediment Input

Complete sediment budgets (input and output) were completed on nine of the sub-watersheds.

In Blueberry Creek watershed, three contiguous sub-watersheds—Bugle Creek, Trident Creek, and Eleven Mile Creek—were sampled with full sediment budgets. Sediment input alone was measured at Nancy Greene and only sediment output was measured at upper Blueberry Creek. In upper Blueberry Creek, a lake exists between sediment sources at upstream logging sites and the sampling point. Because the lake would act as a sediment trap, the creek was sampled to get an estimate of a watershed where the sediment output is likely to be low.

In Little Cayuse Creek, the entire watershed was sampled (sub 1), as well as two upper tributaries (sub 2 and sub 3). The primary stations sampled at Gold Creek were part of the residual area sub-watershed 0, and sub-watersheds 1 and 2. In addition, an erodible section of the mainline road was

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[2] Using the 1995 Interior Watershed Assessment Procedure (IWAP) (B.C. Ministry of Forests and B.C. Ministry of Environment 1995). A new 1999 IWAP was introduced during the course of the study (B.C. Ministry of Forests and B.C. Ministry of Environment 1999).

TABLE 1 *Characteristics of study watersheds*

Watershed	Geology	Soil texture	Sub-watershed	Area (km^2)*	Equivalent clearcut area [a](%)	IWAP hazard rating (version 1995)[b] Peak flows	Surface erosion	Riparian buffers	Mass wasting
Blueberry Creek	Coarse granitic	Mainly sandy	Trident	11.5	28.4	High	High	High	Medium
			Bugle	9.5	26.6	High	High	High	High
			11 Mile	8.9	18.8	High	High	High	High
			Nancy Greene	8.3	41.8	High	High	High	Low
Little Cayuse Creek	Medium metamorphic	Sandy to silty	1	26.5	16.4	Low	High	High	High
			2	4.8	34.2	High	High	High	High
			3	5.9	25.9	High	High	High	High
Redfish Creek	Coarse granitic	Mainly sandy	Total watershed	26.2	10.3	Low	High	Low	High
Gold Creek	Medium sedimentary	Fine sand and silt	0	4.8	0	Low	High	Low	Low
			1	12.5	16.9	High	Medium	High	Low
			2	9.2	16.3	Low	Low	Low	Low
			Total watershed	93.8	10.8	Low	Low	Low	Low

* Watershed areas presented in this table reflect the area above the point of interest in the IWAP. Area values used in sediment budget calculation Tables 4 and 5 are for above the stream sampling location.

[a] Most recent ECA is estimated from reports or Licensees.

[b] B.C. Ministry of Forests and B.C. Ministry of Environment 1995.

surveyed because it was suspected to represent most of the sediment input over the total watershed.

A rapid, road-erosion, survey technique (RREST) was used to quantify the annual sediment input to streams from forestry roads. Road erosion was measured at sub-watersheds in Blueberry Creek in 1997 and 1999, and at all other sub-watersheds in 1998. No survey was carried out in the residual sub-watershed in Gold Creek because all existing roads were overgrown and inaccessible. Sub-watersheds at Blueberry Creek were re-surveyed in 1999.

The RREST procedure uses a detailed survey approach based on measuring sheetwash, rills, gullies, and other erosional features on the road surfaces, cutbanks, fillslopes, and ditches. Full RREST details are presented by Henderson et al. (2000), but the four main steps are:

1. division of roads into homogeneous segments,
2. field evaluation of erosion rates,
3. field evaluation of sediment delivery rates, and
4. calculation of sediment delivery to the channel system.

Following is a brief description of the four RREST steps used in this study.

1. Road segments were delineated based on similar surficial materials and slopes. Segments ranged from about 100 m to >1 km long. Only those roads that could deliver sediment to creeks were selected.

TABLE 2 *Ordinal-scale classification scheme for surface-erosion severity of road running surfaces in the Interior of British Columbia* [a]

Class[b]	Median and range of sediment production rates ($m^3/km^2/y$)	Typical road-surface rill dimensions (depth by width) (cm)	Visual description
1	0.1 0 – <0.3	10 × 0.1	Almost unnoticeable rills, typical of minor sheetwash erosion.
2	1 0.3 – <3	10 × 1	Typical of well-armoured, low-use roads; rills are measurable, but poorly developed.
3	10 3 – <30	50 × 2	Typical of erodible materials, or average-maintenance, high-use roads. Pronounced rill development.
4	100 30 – <300	100 × 10	Severe erosion; access may be difficult by 4WD vehicle but road is not impassable.
5	1000 300 – 3000	200 × 50	Severe gullying, and impassable, but repairable. The result of a major hydrologic event and/or poorly designed or maintained roads.
6	10 000 >3000	500 × 200	Total washout. The result of an exceptional hydrologic event and/or failure of the road-drainage system.

a The descriptions are for the running surface. However, erosion from ditches, cutbanks, and fills can also be included.

b Class 4 and 5 road surfaces are relatively uncommon in the interior, but may be associated with severe cutbank slumping, road surface gullying, or washouts.

2. Table 2 was used as a first approximation to quickly establish road-erosion classes within a watershed. Table 2 is similar to the sediment production Table A3.1 of the 1999 IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). For each road segment, fresh erosion that had occurred in the preceding 12 months was inventoried from diffuse and discrete sediment sources. Diffuse sediment sources included erosion from the running surface, fillslope, cutbank, and ditch line. Discrete, or point, sediment sources included large-scale fillslope slumping or rilling, water-bar or cross-ditch erosion, and cutbank failures with extensive rills or slumps.

   Sediment texture was estimated by hand-texturing material from representative locations in erosion features, such as rills, and sediment-deposition sites. Three classes were used: coarse fragments (i.e., gravel, >2 mm); coarse sand; and fine sand and silt plus clay. Fine sand, silt, and clay are considered together as washload (roughly equivalent to suspended sediment in water samples), and coarser material is bedload. In the study watersheds, sand was considered to be equal parts "coarse" and "fine," and particles <0.5 mm diameter are washload.

3. Sediment entering streams, or deliverability,[3] was determined by estimating the percent of erosion produced to the edge of the road multiplied by the percent connectivity to the stream. This was estimated by comparing the grain-size distribution of original and deposited sediments between the road and stream. Although the evaluation of connectivity required judgement, the detailed field studies by Jordan and Commandeur (1998) helped us calibrate our assessment.

   An example calculation of deliverability is: where there is erosion of 10 m^3 of fines within the road prism to a culvert inlet, if the connectivity to the stream is 20%, then the deliverability would be 2 m^3.
4. Erosion and connectivity were recorded in the field. Following fieldwork, the sediment delivered to a stream channel was calculated using a simple spreadsheet to facilitate data management. Results were evaluated to determine if they were reasonable.

   In this study, the RREST was applied to 10 sub-watersheds plus one mainline road in Gold Creek. In addition to road-erosion measurements, each road section was inventoried for attributes such as level of deactivation, usage (active vs. light temporary), running surface width, and gradient. A total of 158 road sections were surveyed on a total road length of 133 km.

3.2 Sediment Output

Sediment output was measured in most of the same sub-watersheds where sediment input from roads was assessed using the RREST. Exceptions were upper Blueberry Creek, where sediment was sampled for yield but not for input, and Gold Creek, where the whole watershed was sampled for output, but only the mainline road was assessed for input. Water samples were collected and streamflow was measured in the 1998 and 1999 runoff seasons.

The following eight steps were used to calculate sediment output at streams:

1. A staff gauge was installed in the sub-watershed stream (if a hydrometric station was not available).
2. Water samples were collected during the freshet and the main runoff season; samples were taken daily during peak streamflow.
3. Water samples were analyzed for turbidity; any sample with >1 NTU was analyzed for suspended sediment.
4. A stage discharge relationship was established using discharge measurements and staff gauge height. Approximately 10 streamflow measurements were made during a range of discharge.
5. Daily discharge was measured or estimated for the entire runoff period of April 1 to September 31, for both 1998 and 1999. Discharge data from nearby continuous recording stations were used to assist in estimating daily discharge.
6. The turbidity-versus-suspended-sediment relationship was established using regression equations. A separate relationship was established for each station. The suspended-sediment-versus-discharge relationship was subsequently established at each station using regression equations. Using those equations, daily suspended-sediment concentrations were predicted for each day of the year for which measurements were not available.

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[3] Often referred to as delivery ratio in the literature.

7. During the runoff period of April 1 to October 31, for both 1998 and 1999, sediment load was calculated for each day by multiplying suspended sediment by discharge and a constant (to account for units).
8. The seasonal sediment load was calculated as the sum of the daily loads.

The general approach was to take daily samples of the water at each stream during the spring freshet, which is when most of the annual sediment load in streams with a snow-dominated hydrograph is transported. At each stream, samples were taken about 50–100 times during the 183-day runoff season of April 1 to October 31, with the majority collected between mid-April and mid-June. Thereafter, water was sampled less frequently, such as bi-weekly after the freshet period and then monthly during low flows in summer and fall.

At the Nelson Forest Region office, all water samples were analyzed for turbidity using a Hach 2100N turbidity meter. Any sample with turbidity of 1 NTU or greater was analyzed for suspended sediment at the Environment Canada laboratory in Edmonton, Alberta, or at a commercial laboratory.

Discharge was measured at most study streams using staff gauges and by establishing a stage discharge relationship between measured streamflow and a range of staff gauge heights. In two streams (Trident Creek in Blueberry Creek watershed, and sub 01 in Gold Creek watershed) a recorder was installed, and this continuous record was used to improve estimates of streamflow between sampling dates. In the Blueberry Creek sub-watersheds, streamflow measurements were problematic, particularly at high flows, therefore the Trident Creek continuous data were used to estimate streamflow at the watershed's other creeks by applying a drainage area ratio.

A graph of the log of turbidity versus the log of suspended sediment yielded the best relationship for estimating suspended sediment from turbidity. This is a useful relationship to develop because turbidity alone can be measured in future years and it is much less expensive to measure than suspended sediment.

Daily sediment load was calculated as the product of discharge and sediment concentration. Sediment load for days without water samples was estimated using the relationships derived between turbidity and suspended sediment and between discharge and suspended sediment. Total sediment load was calculated by summing daily sediment, expressed as tonnes. When divided by sub-watershed area, the sediment yield is t/km^2/y.

4 RESULTS

4.1 Sediment Production

Most of the erosion was surveyed on a small portion of the total road length. The 37 km of road in Erosion Severity Classes 3 and 4 accounted for 84% of the total erosion measured from all 133 km of roads (Table 3). The single Class 4 road section in Trident Creek alone accounted for 32% of the total sediment produced at roads, yet was only 1.3% of the total road length.

4.2 Sediment Deliverability

The estimated sediment delivery to streams averaged 36% of total sediment production from roads over the surveyed watersheds (Table 4). Approximately 91% of the total amount of sediment input from diffuse sediment sources was from roads in Erosion Severity Classes 3 and 4. The remaining 9% of sediment originated at Class 1 and 2 roads.

TABLE 3 *Volume of erosion (m^3/y) by Erosion Severity Class*

		Erosion Severity Class			
Watershed	**Sub-watershed**	**1**	**2**	**3**	**4**
Blueberry Creek	Trident	0.1	2.8	68.6	137
	Bugle	0.3	4.8	31.2	0
	11 mile	0.3	3.2	11.0	0
	Nancy Greene	0.1	8.1	41.6	0
Little Cayuse Creek	Sub-1[a]	1.3	26.5	21.5	0
	Sub-2	0.2	6.6	3.1	0
	Sub-3	0.2	0	0	0
Redfish Creek	Total watershed	0.4	10.2	15.9	
Gold Creek	Sub-0[b]	0	0	0	0
	Sub-1	1.1	0	0	0
	Sub-2	0.3	0	9.7	0
	Mainline	0.4	10.3	15.9	0
Total		4.4	65.9	215.4	137.0
% of total		1.0	15.6	51.0	32.4

a Sub-1 data in Little Cayuse Creek watershed were used alone to calculate column totals because data include all roads in Sub-1, Sub-2, and a residual area of the watershed.

b No roads.

TABLE 4 *Sediment production and deliverability to streams*

			Production at roads		Delivered to stream		
Watershed	**Sub-watershed**	**Area (km^2)**	**Tonnes**	**Tonnes/ km^2**	**Tonnes**	**Tonnes/ km^2**	**% of sediment production**
Blueberry Creek	Trident	11.5	367.2	31.9	128.1	11.1	34.8
	Bugle	9.5	64.3	6.8	26.5	2.8	41.2
	11 Mile	8.9	44.1	5.0	22.4	2.5	50.8
	Nancy Greene	8.3	81.2	9.8	6.2	0.8	7.6
Little Cayuse Creek	Sub- 1	15.8	90.4	5.7	27.5	1.7	30.4
	Sub- 2	4.8	17.7	3.7	3.2	0.7	18.0
	Sub- 3	3.6	7.5	2.1	6.6	1.8	88.0
Redfish Creek	Total watershed	26.2	56.3	2.1	18.2	0.7	32.3
Gold Creek	Sub-0	4.8	0.2	0.0	0.0	0.0	0.0
	Sub- 1	12.5	2.5	0.2	0.08	0.01	3.2
	Sub- 2	9.2	16.1	1.8	0.14	0.02	0.0
	Total Watershed	93.8	188.6	2.0	101.9	1.1	53.6

Delivered sediment ranged from near 0% in sub-0 and sub-2 in Gold Creek up to 88% at Little Cayuse Creek (erosion from point sediment sources such as a deactivated ford), depending on the connectivity to streams. Either diffuse or point sediment sources were responsible for sediment delivery, depending on a combination of factors such as road engineering, travel time to creeks, and sediment-storage opportunities. In general, however, it was found that slope gradient and distance between the road and creek were important factors influencing sediment entering streams at road sections with active erosion.

The deliverability was much lower in the Gold Creek sub-watersheds than the other watersheds. This is due to lower sediment production and minimal connectivity between the roads and streams. Another factor could be the fractured bedrock, which results in ditch drainage infiltrating rather than transporting sediment towards the stream (Jordan 2001).

4.3 Sediment Yield

Calculation of sediment yield is illustrated in Figure 2, using 1999 discharge data from Trident Creek as an example. The relationship between turbidity and streamflow is illustrated in Figure 2a, daily concentrations are shown in Figure 2b, and Figure 2c displays the seasonal sediment load. It can be seen that most of the sediment is transported at the highest streamflows. Similar graphs were calculated for all sub-watersheds in this study (not shown). The total seasonal sediment yield (Table 5) is the sum of the daily loads illustrated in Figure 2c.

Average suspended sediment yield at the study creeks ranged from 0.8 to 5.8 $t/km^2/y$ over the 2-year sampling period (Table 6). Average values are within the range of sediment yields measured at other watersheds in the British Columbia interior (Table 7) and are towards the low end of the main trend line for watersheds in the entire province (Figure 7b in Church et al. 1988).

Water quality at all study sub-watersheds was typically within standards for turbidity and drinking water (Table 8).[4] Turbidity rarely exceeded 5 NTU, which is the recommended maximum for creeks providing drinking water in Canada. Turbidity exceeding this maximum occurred during peak flow: after approximately July 1, water turbidity was always <5 NTU. Although there was no trend between watershed geology and sediment yield, there was a small trend between watershed geology and turbidity. The watersheds with finer-textured sediment (Little Cayuse and Gold creeks) tended to have more occurrences of water samples with turbidity >1 and 5 NTU (Table 8).

4.4 Sediment Budget

The sediment budget derived for the study watersheds indicates that more sediment output was measured at streams than input (Table 9). Note that the budget equation applies to same-year sediment input and output measurements.

The difference between measured sediment input to streams from roads and sediment yield can be partly accounted for by measurement error, and by unmeasured natural sources of sediment originating from hillslopes adjacent to streams and from streambank erosion. This is shown as "residual" sediment in Table 9. We suspect that much of the residual sediment load is due to bank erosion of nearby channel sources. Residual sediment ranges from 21.7% in sub-3 of Little Cayuse Creek to 100% in sub-0 and sub-1 at Gold Creek. The residual sediment usually accounts for more than 70% of the annual load in the study watersheds. The magnitude of the measurement error is estimated and discussed in the following section.

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[4] Sample size ranged from 48 to 102/site/y.

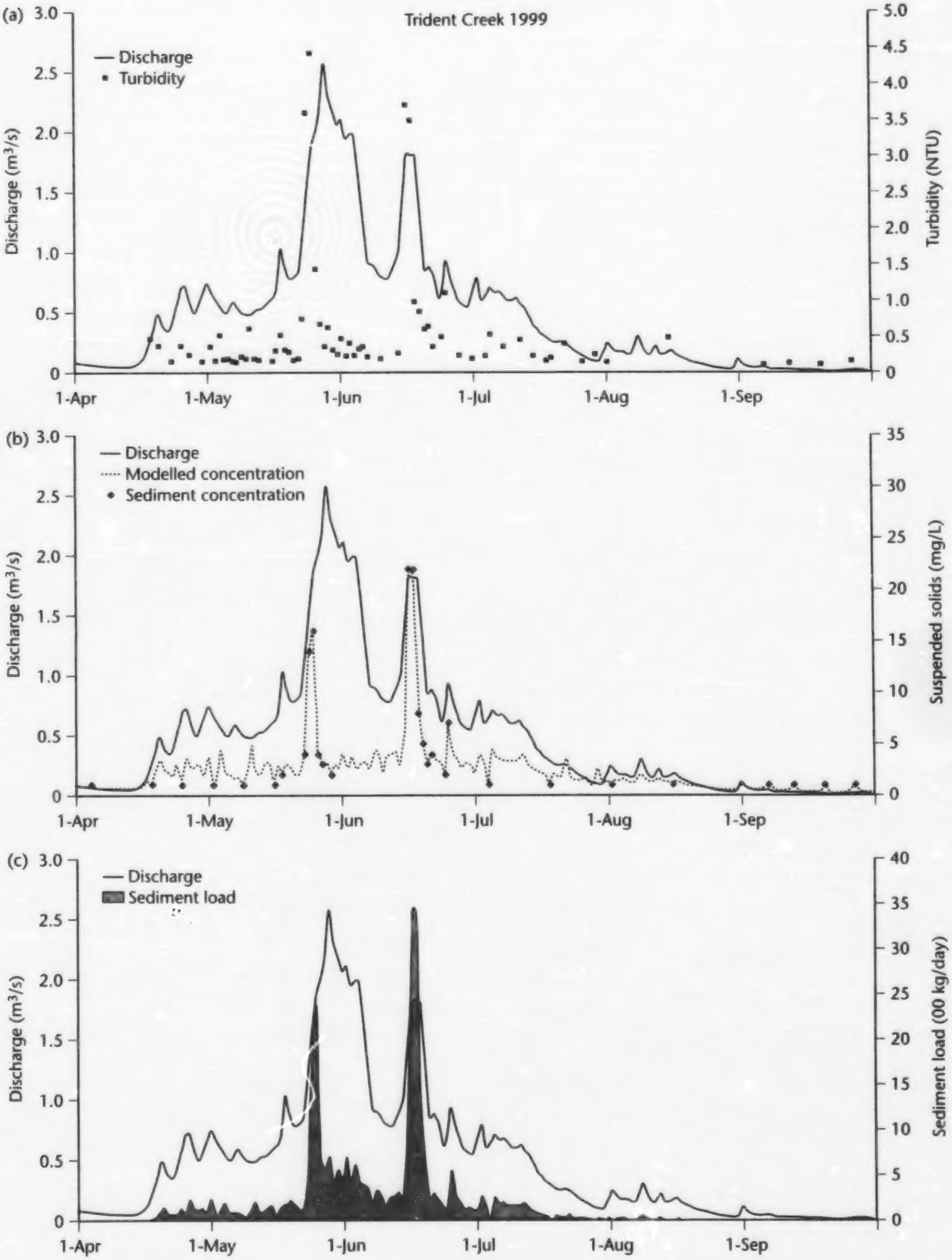

FIGURE 2 *This set of graphs illustrates the sediment budget calculation process for Trident Creek in 1999. The upper graph shows discharge and turbidity data. The middle graph shows the measured and calculated sediment concentrations. The lower graph shows the sediment load, which is calculated by multiplying sediment concentration by discharge. Note that most of the load is carried in a few days with the highest discharge.*

TABLE 5 *Sediment yield (tonnes/km^2) at study watersheds*

Watershed	Sub-watershed	Area (km^2)	Sediment yield 1998	Sediment yield 1999	Sediment yield Average
Blueberry Creek	Trident	11.5	2.4	2.8	2.6
	Bugle	9.5	3.3	4.4	3.9
	11 Mile	8.9	0.8	1.3	1.1
	Upper Blueberry	26.3	0.8	0.9	0.8
Little Cayuse Creek	Sub- 1	15.8	5.8	2.7	4.3
	Sub- 2	4.8	2.4	1.3	1.9
	Sub- 3	3.6	2.3	3.1	2.7
Redfish Creek	Total watershed	26.2	5.6	9.6	7.8
Gold Creek	Sub-0	4.8	1.3	1.3	1.3
	Sub- 1	12.5	n/a	1.7	1.7
	Sub- 2	9.2	5.7	4.9	5.3
	Total watershed	93.8	2.8	2.5	2.7

TABLE 6 *Sediment yields at interior British Columbia watersheds*

Watershed	Area (km^2)	Sediment yield (t/km^2/y)	Data source
Anderson	9.1	3.3 [a]	Church et al. 1988
Five Mile	47.5	7.7 [a]	Church et al. 1988
Duck	57	6.6 [a]	Church et al. 1988
Arrow	78.7	8 [a]	Church et al. 1988
Laird	15	3.9[b]	Jordan and Commandeur (1998)
Deer	80.5	10	Jordan and Fanjoy (1999)
Redfish	26.2	6.2[b]	Jordan and Commandeur (1998)
Study watersheds in present study	3.6–93.8	0.7–5.3 [c]	Table 5

a Mean specific sediment yield over the period of record, which ranges from 3 to 7 years.
b Average over the period from 1993 to 1996.
c Average over 2-year period, 1998–1999.

TABLE 7 *Number of water samples exceeding 5 NTU and 1 NTU. Sample size was typically between 50 and 100 samples. All values greater than 5 NTU occurred during the freshet period*

		Turbidity			
		> 5 NTU		> 1 NTU	
Watershed	**Sub-watershed**	**1998**	**1999**	**1998**	**1999**
Blueberry Creek	Trident	0	0	8	6
	Bugle	1	2	12	9
	11 Mile	0	0	1	4
	Nancy Greene	0	0	1	3
Little Cayuse Creek	Sub- 1	2	0	36	29
	Sub- 2	1	1	45	33
	Sub- 3	0	0	8	3
Redfish Creek	Total watershed	3	4	14	6
Gold Creek	Sub-0	1	1	16	25
	Sub- 1	n/a	3	n/a	51
	Sub- 2	6	6	20	28
	Total watershed	5	2	26	21

TABLE 8 *Sediment budget (t/km^2) at study watersheds*[a]

Watershed	**Sub-watershed**	**Sediment input**	**Sediment output**	**Residual**[b]	**Residual as % of sediment output**
Blueberry Creek	Trident	0.2	2.8	2.6	93
	Bugle	2.8	4.4	4.1	93
	11 Mile	2.5	1.3	1.2	92
Little Cayuse Creek	Sub- 1	1.7	5.8	4.1	71
	Sub- 2	0.7	2.4	1.7	71
	Sub- 3	1.8	2.3	0.5	22
Redfish Creek	Total watershed	0.7	7.6	6.9[a]	91
Gold Creek	Sub-0	0.0	1.3	1.3	100
	Sub- 1	0.006	n/a	n/a	n/a
	Sub- 2	0.02	5.7	5.7	100
	Mainstem[b]	1.1	2.8	1.6	57

a Using same-year sediment input and yield data.

b Residual sediment not measured. It is the difference between output and input, accounted for by natural sediment sources at streambanks.

TABLE 9 *Report-card data for study watersheds*

		Numerical indicators for IWAP report card [a]						Sediment input	
Watershed	**Sub-watershed**	**1. ECA (%)**	**3. Road density km/km²**	**4. Length of road as high sediment source km/km²**	**5. Landslides**	**6. Length of road on unstable slopes (km)**	**7. Stream crossings**	**Tonnes**	**Tonnes/km²**
Blueberry Creek	Trident	28.4	1.5	2.9	0	2.5	7	128.1	11.1
	Bugle	26.6	1.1	1.6	0	0.75	9	26.5	2.8
	11 mile	18.8	1.5	0	0	5	6	22.4	2.5
	Nancy Greene	41.8	2.7	0	0	0	6	6.2	0.8
Little Cayuse Creek	Sub-1	16.4	1.3	0	3	2.3	10	27.5	1.7
	Sub-2	34.2	2.9	0	1	0.9	13	3.2	0.7
	Sub-3	25.9	1.8	0	0	0	7	6.6	1.8
Redfish Creek	Total watershed	10.3	0.9	0	5	4.9	24	18.2	0.7
Gold Creek	Sub-0	0	0	0	0	0	0	0	0
	Sub-1	16.9	1.5	0	0	0.4	5	0.08	0.01
	Sub-2	16.3	1.2	0	0	1.6	3	0.14	0.02
	Total watershed	10.8	1.2	3.9	0	5.1	59	101.9	1.1

[a] The number at each indicator refers to the corresponding number in Table 1 of the IWAP.

5 DISCUSSION

Although sediment input varied over three orders of magnitude, sediment output was similar between sub-watersheds, within the same order of magnitude and usually within a factor of two. The group of watersheds that were surveyed, however, had large variations in indicators that are often used to estimate sediment input such as road densities, number of stream crossings, unstable terrain, and levels of past logging (Table 9). Road density, for example ranged from 0 to nearly 3 km/km², and ECAs at logged watersheds ranged from 7.5 to 34.2%. Yet sediment output and water quality were remarkably similar across watersheds and also very similar to other unlogged or nearly unlogged watersheds in the region (listed as the first five in Table 6). This would indicate that the sediment output is close to natural background levels despite the differences in levels of watershed development.

Hydrologists have relied less on watershed indices to estimate sediment input since the introduction of the first version of IWAP in 1995 (B.C. Ministry of Forests and B.C. Ministry of Environment 1995), but numerical data are still inventoried in a report card of the 1999 IWAP (B.C. Ministry of Forests and B.C. Ministry of Environment 1999). However, when we compared report-card data for numerical indicators such as road density, ECA, and others listed earlier against measured sediment input in the study watersheds, the numerical indicators did not relate in a consistent manner to measured data (not shown).

Our method for sediment input closely follows the 1999 IWAP procedure to determine a sedimentation-hazard table, except that the IWAP provides a text description for sediment delivery and we quantified it. In a review of our sediment-production and input results for Class 3 and 4 roads, we suggest that a road section with 5 $m^3/km^2/y$ or greater sediment input is a match to the minimum "High" sedimentation-hazard standard that is mapped in an IWAP report. The drawback to this minimum threshold is that sediment sites with lower than 5 $m^3/km^2/y$ would not, therefore, be a highlighted problem area in an IWAP, but it could still represent a concern for sediment input on a cumulative basis. Regardless, we feel that our results validate the method of the sedimentation-hazard table generated from Table A3.3 of the 1999 IWAP, which was one of the objectives of the study.

The RREST method, therefore, is useful for quantifying the most significant sediment sources to creeks and for identifying high-hazard areas of diffuse and point source erosion from roads. Stabilizing sections of Erosion Severity Class 3 or higher to Erosion Severity Class 2 or 1 could, theoretically, result in a geometric reduction in the amount of sediment production and input to streams. Most of the measured sediment yield in the study streams, however, was attributed to natural loads transported during the freshet period. This would tend to indicate that road-rehabilitation efforts will have limited effect in improving water quality and reducing sediment load on an annual sediment-yield basis or in a small sub-watershed. The effectiveness of rehabilitation works applied to roads in reducing sediment input to streams would likely be below detectable limits in a stream-sampling program in interior British Columbia watersheds similar to those in this study, except where water-quality impacts are greater in comparison to background levels.

The overall, high water quality and undetectable impacts of forestry-related sediment input also pose difficulties for the professional hydrologist, who must use judgement to extrapolate results from sediment-hazard sites to produce a basin-level, sediment-hazard rating. Our results would tend to indicate that many hydrologists are giving too much consideration to older, relatively inactive sediment sources in the assessment of hazard.

Despite the overall, low measured impact of forestry roads on water quality in this study, we recognize that forestry roads can increase sedimentation to streams. This is especially true when landslides or large fillslope failures can dominate a sediment budget in the event year. At peak flows, sediment input from roads is less detectable in a water-sampling program because this is when natural sediment loads are highest. At low flows, water is usually very clear, and impacts of forestry activities to water quality may be more obvious. This was the case at Gold Creek sub-watershed 1, which registered low turbidity (~1 NTU) in water for several weeks during upstream road construction (Figure 3). The road was located close to the water-sampling location, and careful attention was given to controlling sediment at the road. Although not a concern for water quality, the low amount of sediment input would not have been separated from natural levels during peak flows, nor would this likely have been detectable if the road was located further upstream.

Hydrologists using sediment budgets and forestry managers interpreting results should be aware of method limitations. Results should be considered as estimates because there are many potential sources of error. For example, the connectivity must be estimated because measurements are extremely difficult and expensive. There may be considerable sediment output that is

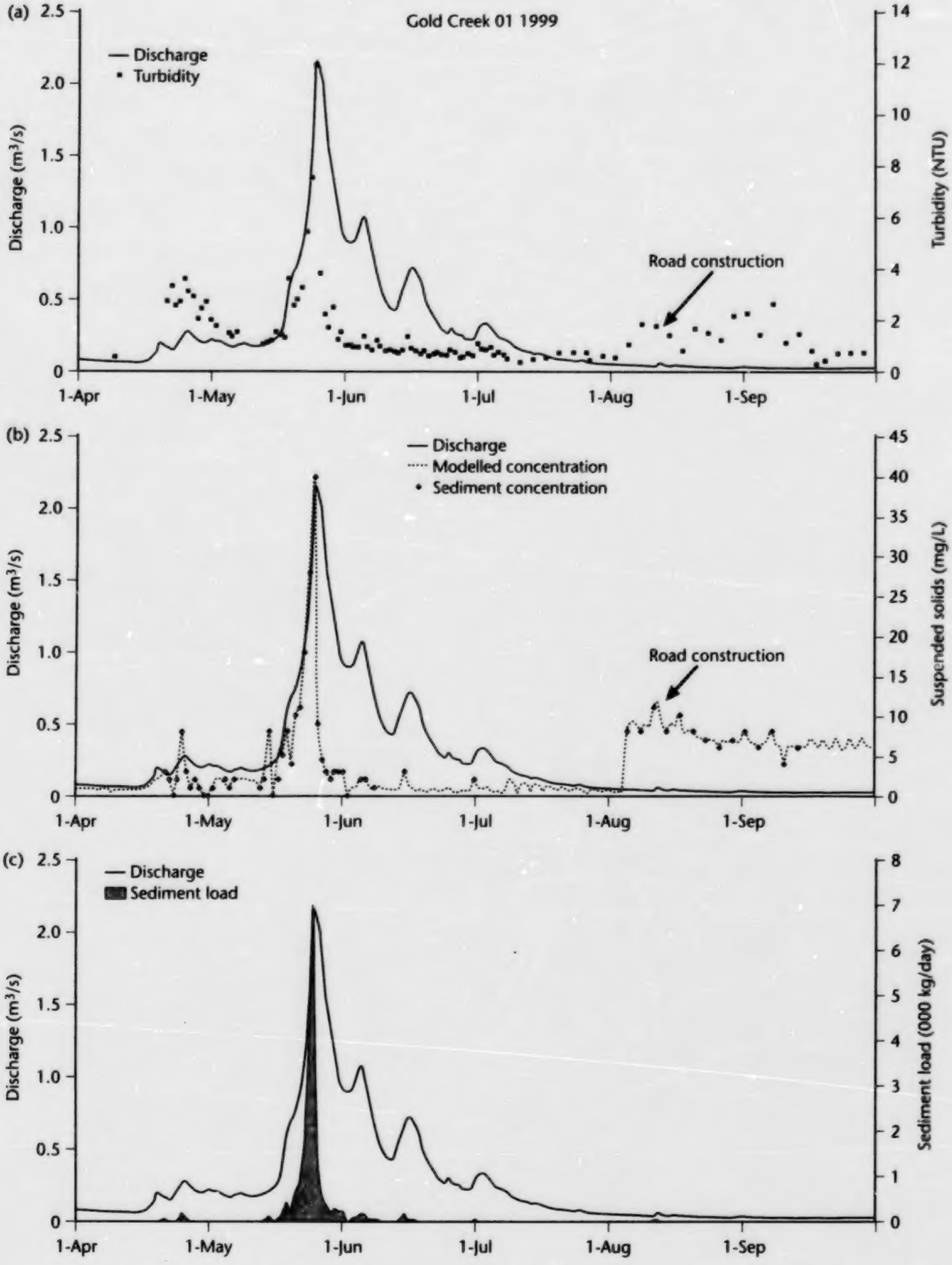

FIGURE 3 *This set of graphs shows the turbidity, suspended sediment concentrations, and sediment load in Gold Creek 01 in 1999. Note that there was an incident where turbidity and suspended sediment concentrations were increased in early August. The increased suspended sediment did not significantly increase sediment load because flows were low.*

not measured because it is not captured in the daily samples. Also, there can be a wide year-to-year variation in flow, so it is hard to judge the representativeness of a single measurement year.

Survey error is estimated at close to an order of magnitude. For example, using the RREST, subjectivity was found by comparing results between six surveyors, who completed field estimations of gross erosion and deliverability over the same three road sections. Absolute amounts of sediment were negligible in terms of sediment input to streams for Class 1 and 2 roads, but this became important for roads at Erosion Severity Class 3 or higher. At Redfish Creek, Tutsch (1998) compared RREST results with more thorough surveys and found that surveyors overestimated connectivity to streams. This emphasizes the need to walk all sediment trails to creeks from roads, which are best visualized during spring surveys or after storm events. Seasonally, a road survey carried out in the spring may miss sedimentation effects of fall storms, while surveys in the summer/fall may result in sediment trails between roads and creeks becoming too overgrown to assess. Despite these limitations, Tutsch (2000) noted that results from both RREST and the more rigorous survey at Redfish Creek were close, within a factor of two. Active haul roads that are frequently graded can also be assessed using the RREST, but would require surveying more than once annually to obtain realistic results.

The annual variation in snowmelt rates and peak runoff can result in dramatic differences in both sediment delivery from roads and stream runoff. In our study we surveyed a road section in 1997 and again in 1999 in Blueberry Creek. The 1999 results were a small fraction of the 1997 survey. We attribute this difference to the high runoff in 1997. Field data collected in the year of question could therefore represent a sample point of time along a probability curve of events. Therefore, results should be interpreted in context of the current hydrologic year and dynamics of watershed use.

Another factor to consider is that sediment sources remain visible long after they are producing significant sediment. A hydrologist may infer continued erosion based on evidence of past erosion, but this inference may not necessarily be valid. A number of other studies have found that road impacts are most severe in the first year after construction or unusual flood (e.g., Reid and Dunne 1984), but decline rapidly thereafter.

Water-sampling programs are also subject to error from estimations of daily loads using single grab samples. We collected between 50 and 120 samples at each station. This is often the practical limit for an operational sampling program, but it is the minimum number of samples required to characterize the yield. Yet there is a diurnal variation and there could be considerable variation between daily samples. Short-duration events such as landslides and point sediment inputs may also be missed, and pulse through the system between discrete measurement times. All these are significant error sources inherent to sediment budgeting, and they need to be considered when weighing efficiencies against cost.

5.1 Cost

For IWAP purposes, the field portion of the RREST can be streamlined to calculate sediment input by surveying only those road sections (or a reasonable sub-set) connected to streams. Field studies indicated that a small portion of the total road network (e.g., 10–20%) would account for 80–90% of the annual sediment input from roads.

The RREST survey can be completed in 1 to several days, depending on accessibility, watershed size, and amount of high erosion severity road sections needing field traversing. Persons with limited experience in soil texturing can be trained in the RREST in 1–2 days. There are also planning and report costs, but we suggest that $1500–$3000 per sub-watershed may be required for the initial survey. Subsequent surveys are much quicker because road sections are already established, along with a map showing point and diffuse sediment sources.

Selecting and setting up of stream stations for discharge and water sampling can cost between 3000 and $8000 per station in the first year, depending on labour accessibility, stream size, and water quality. Establishing rating curves is a major target of the first year. If the program is successful in the first year, the cost can reduce to $2000–5000 in subsequent years.

Utilizing residents of the watershed to conduct water sampling helps reduce costs; it also helps establish goodwill with the residents and thereby increases the credibility of monitoring programs requested by watershed-assessment committees. Finally, calculations of the data may also form an important cost, especially if estimates require modelling.

Financial aspects of operating a watershed sediment budget can be weighed against the benefits obtained by such a program. Benefits may be measurable, such as reductions in sediment input. Intangible benefits include an increased confidence in the ability of forestry operations to protect water quality. Most importantly, the sediment-budget method helps answer the following frequently asked questions posed by watershed committees. Where are the most significant sediment sources in a watershed? Where should sediment-control strategies be focussed? How effective has the road-deactivation program been in reducing sediment delivery to creeks? How much fine-textured soil is expected to wash off old roads? How variable is water quality? Where should watershed-restoration dollars be best applied?

A watershed sediment budget is probably best used where the sediment problems are thought to be severe.

6 CONCLUSIONS

We examined the pattern of sediment input to streams from roads in 11 watersheds and sub-watersheds in southeastern British Columbia between 1997 and 1999 and the sediment yield in streams in the same watersheds between 1998 and 1999. Using average values for the study watersheds, approximately 74% of sediment mobilized from roads were re-deposited either on the road or between the road and stream, resulting in an average of 36% of the gross erosion reaching streams. Two-year sediment yield from streams ranged from 0.9 t/km^2/y to 5.3 t/km^2/y and are within the range of values reported for other logged and unlogged watersheds in interior British Columbia. Trends between sediment yield and watershed characteristics such as ECA, road density, soil texture, and other numerical indicators of watersheds were not apparent.

The sediment-source survey technique in the 1999 IWAP is an improvement on the reliance of surrogate indices used in the 1995 IWAP. When combined with point sediment sources, the most significant sediment sources in a watershed are identified. We suggest that approximately

5 $m^{3/}km^2/y$ of sediment input quantifies the current textual description of the 'High' hazard in the sedimentation hazard table of the 1999 IWAP.

The water-sampling program showed that water was of high quality with respect to turbidity. There were few days with turbidity levels greater than 5 NTU, which is the upper-limit standard for drinking water in Canada, and these were restricted to a short period during the spring freshet. Slightly more samples had moderately high turbidity in the fine- and medium-textured watersheds of Gold Creek and Little Cayuse Creek.

The sediment budgets completed on nine of the watersheds show that much more sediment leaves the watershed than is put in from erosion at forestry roads. Sediment that enters streams from roads was measured and it represented an average of 24% of the total sediment yield in watersheds (range is 0–88%). In streams, background levels of sediment from natural sources such as bank erosion usually greatly exceeded sediment produced at forestry roads. Therefore, measured sediment-input levels, or rehabilitation efforts to stabilize road erosion, would not likely be detectable in a stream-sediment sampling program because of high natural sediment loads, especially during the freshet period. The sediment-budget technique is therefore useful to address water-quality issues in forested watersheds, but development-related sediment impacts may not be discernible except when input levels exceed background values.

7 ACKNOWLEDGEMENTS

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Assessing Natural Sedimentation Patterns and Impacts of Land Use on Sediment Yield: A Lake-sediment–based Approach

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ABSTRACT

Lake-sediment records were used to investigate historical sedimentation patterns in 70 headwater lake catchments of northwestern British Columbia. Sediment-core chronologies and sedimentation rates were derived from ^{210}Pb dating methods. Study objectives include the confirmation of lake coring and associated analysis techniques as appropriate methods for reconstructing past sedimentary environments, the assessment of the natural patterns of lake sedimentation, and the determination of the relative impact of forestry and other land-use disturbances on lake sedimentation in context with the naturally observed variability.

Several interesting lake-sediment records have been identified and reviewed. While there is a high degree of variability in the data set, several distinct trends were recognized. Regional analysis has revealed that specific sediment yield spans two orders of magnitude, from 0.55 t/km^2/y in the Interior Plateau to 52 t/km^2/y in the Coast Mountains. Lake basins are differentiated by physiography, both in terms of average specific sediment yield and dominant processes of sediment transfer, as indicated in the drainage-basin, area-specific, yield relations. Temporal analysis has indicated a trend towards increasing lacustrine sedimentation rates irrespective of land-use change in the study watersheds. This trend may be related to precipitation increases in the study area over the last several decades. Episodic natural disturbances are very important processes of sediment transfer in headwater lake catchments, especially in mountainous regions. Land-use impacts could be only partially separated from natural fluctuations; however, a signature of land use was observed in some of the study lakes that were exposed to high levels of land-use disturbance.

INTRODUCTION

It has long been established that land-use disturbances can induce elevated sediment yields in affected drainage basins. Increased sediment yields caused by forestry-related activities can have adverse effects on aquatic ecosystems in both streams (Scrivener et al. 1998) and lakes (Miller et al. 1997). Dominant processes, efficiency, and rates of sediment transfer vary greatly throughout the Pacific Northwest in response to topographic, geologic, and climatic factors (Swanson et al. 1987). The complex behaviour of sediment transfer in the Pacific Northwest holds profound implications in the study of how forestry affects sediment yield.

A major problem encountered in studying disturbed sediment yields in the Pacific Northwest is separating the forestry impacts from natural disturbances, given the high degree of natural spatial and temporal variability encountered. It has been demonstrated that the analysis of lake sediments can be useful for assessing land-use impacts on sediment yield at the basin scale, since a long-term sedimentary record can be established that reflects all of the integrated upstream watershed effects (Arnaud 1997). This is especially beneficial in remote mountainous regions where stream gauging and long-term monitoring is non-existent. In this study, lake-sediment records have been utilized to investigate historical sedimentation patterns in northwestern British Columbia. The specific project objectives are as follows:

1. Confirm the usefulness of lake coring and associated analysis techniques as appropriate methods of assessing long-term impacts of forest harvesting and other land-use disturbances on lacustrine sedimentation.
2. Assess the natural patterns of lake sedimentation, including regional trends, spatial scale effects, and temporal variability.
3. Determine the relative impact of forestry on lake sedimentation in context with the naturally observed variability.

The key premise of this study is that linkages exist between the inherent landscape characteristics and terrestrial disturbances (both natural and anthropogenic) of lake catchments and the quantity of accumulating lacustrine sediments. Lake sediments represent a historical record of sediment yield and sediment characteristics from the contributing drainage basin area. Petts and Foster (1985), Foster et al. (1987), and Foster et al. (1988) have reviewed and demonstrated the lake-sediment framework and its application in reconstructing past catchment conditions. When properly sampled and analyzed, the information recorded in the sediments can be extracted as profiles of historical lake sedimentation. Changes in sedimentation associated with land-use disturbance can then be identified and described.

The primary focus of this research is on the historical rates of lake-sediment accumulation derived from ^{210}Pb analysis of sediment core samples from the study lakes. ^{210}Pb dating is a commonly used technique for establishing sediment chronologies back to 150 years before present. A total of 70 lake catchments were selected for this study. The development and utilization of geographic information system (GIS) databases has been critical for handling the large amount of spatial data required for the project. A GIS database was developed to inventory the landscape data and land-use histories of the lake catchments. Extracted from this database were variables to describe the natural landscape and the land-use history for each study lake. These variables and the lake-sediment data were then analyzed to resolve the three study objectives listed above. The project can be divided into three phases:

1. Collection and analysis of lake-sediment cores in order to establish historical rates of sediment accumulation and measure other sediment parameters for the study lakes.

2. Development of a spatial lake catchment inventory in a GIS environment suitable for the extraction of required landscape and land-use indices for analysis.
3. Correlation analysis of GIS-derived indices with sediment accumulation rates and other sediment parameters in order to interpret regional sedimentation patterns.

This paper presents the key findings of the study to date. A more detailed examination of the data can be found in Schiefer (1999). Additional analysis of the data is currently being considered, including empirical modelling of sediment yield over both time and space using multivariate techniques.

GENERAL STUDY AREA

The study area is situated in northwestern British Columbia between 54° and 56° N and 126° and 131° W (Figure 1). Clague (1984) gives a detailed description of this region in a Geological Survey report on the Quaternary geology and geomorphology of the area. The study region consists mainly of rugged mountainous areas cut by deep valleys. The Coast Mountains contain the most spectacular mountainous terrain in the study area. Moving into the Nechako Plateau to the east, the terrain becomes more rolling with less exposed rock outcrops. Topography and the predominant flow of moisture-laden air from the west control precipitation in the study area, with the Coast Mountains receiving the highest annual precipitation during frequent mid-latitude cyclonic storms in the winter months. Most of the area below 1500 m was forested prior to human settlement, but large sections of accessible valleys and plateau areas have been cleared during the 20th century to support the forest industry and other land-use activities.

METHODS

Lake Selection

The British Columbia Ministry of Environment, Lands and Parks provided a preliminary list of several hundred potential headwater study lakes for this project. Topographic maps, lake inventory reports, and air photos of the region were examined in order to reduce the list of candidate lakes. Site selection involved consideration of lake suitability for a sediment-based, sediment-yield study based on lake morphometry and landscape characteristics of the lake catchment. Lakes had to be deep enough (preferably >10 m) to minimize the potential for physical reworking of sediments from waves, seasonal overturn processes, subaqueous slumping, and bioturbation by bottom-dwelling organisms. Lakes also had to be large enough to be accessible by floatplane and small enough that a single core will represent a fair and consistent index of sediment yield to the lake (i.e., approximately 1 km^2). Complex bottom morphology leads to greater within-lake spatial variability of sedimentation patterns, making estimates of sediment yield using a single core unreliable. Both landscape and land-use characteristics of the lake catchments were considered in the lake-selection process in order to ensure that the study lakes were well representative of lakes in northwestern British

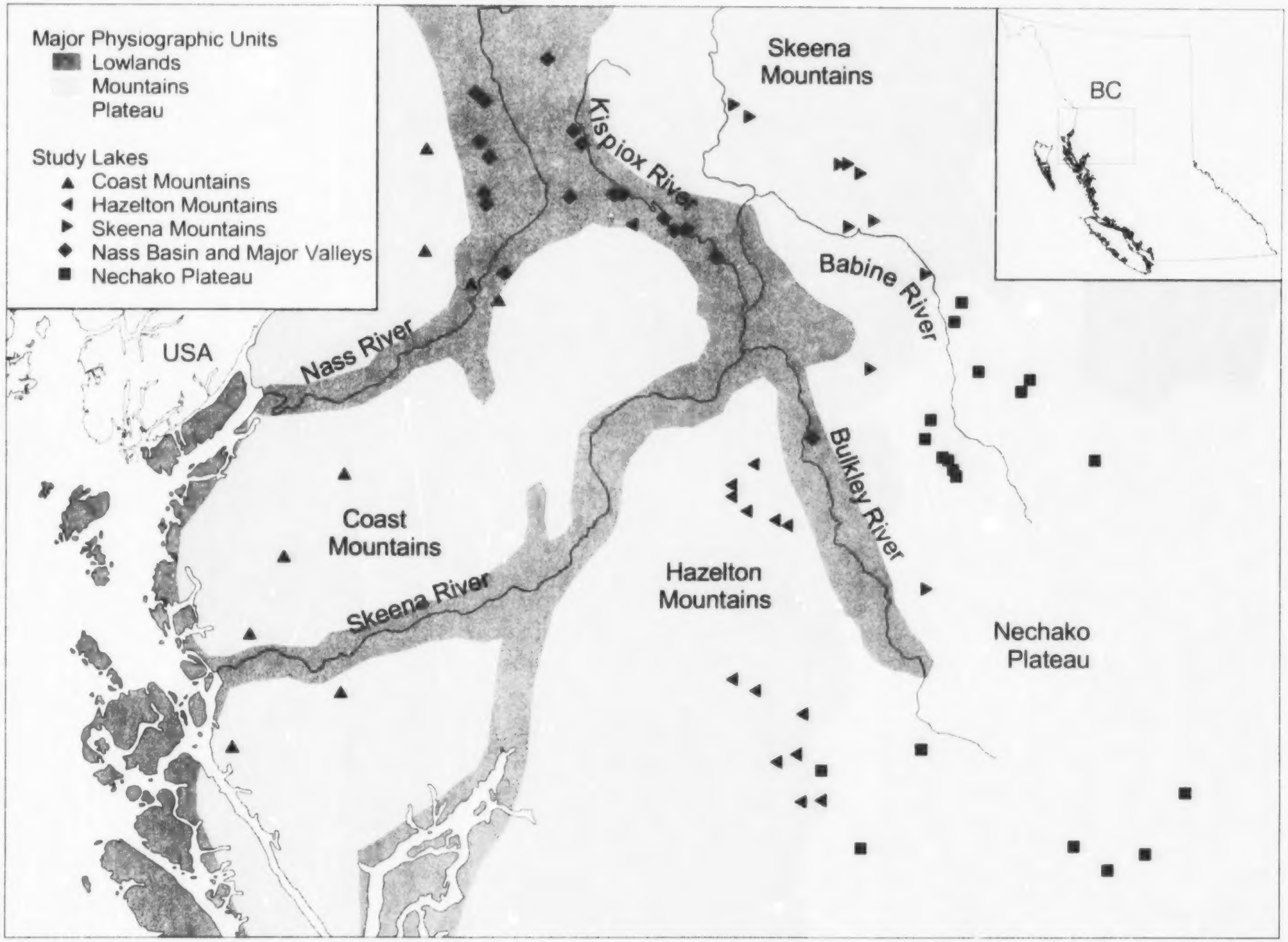


FIGURE 1 *Skeena region study area.*

Columbia. First- to third-order catchments were selected from a variety of physiographic regions in the study area, including coastal, mountainous, plateau, and major valley regions. Unforested high-alpine and glacier lakes were not included in this study. Significant effort was also made to include lakes subjected to a gradient of forestry-related, land-use disturbances. Ultimately, field reconnaissance was used to determine the final list of study lakes. A total of 70 small lake-catchments (order of 10–100 km^2) were selected for the project.

Sediment Coring

Coring of lake-bottom sediments using a modified Kajak-Brinkhurst (KB) gravity corer was a major component of the field work. A detailed description of the KB corer is provided by Brinkhurst (1974). Upon arrival on each of the study lakes, depth sounding was conducted along the entire length of the lake to characterize the basin. Sediment-sampling sites were always situated at the deepest point of the lake basin. Sediment cores retrieved from deep and stable sections of the lake bottom usually have the finest stratigraphic definition as a result of sediment focusing of the fine materials (Pack et al. 1997). Four cores were collected at each station for dry-bulk density analysis, ^{210}Pb dating, archiving, and a backup in case of loss. After all of the cores were collected, they were aligned to ensure that they were consistent in terms of apparent layering and other sediment characteristics. To visually assess the areal continuity of the lake-bottom sediments, additional cores were sampled at a variety of other mid-lake locations as time permitted.

Core extrusion and slicing was performed using the OPS Core Extruder. Sediment samples were extracted from the top of the core using a sectioning device. The core sub-samples were then washed into pre-labelled sample bags using distilled water, and submitted for laboratory analysis.

Laboratory Analysis and Yield

^{210}Pb dating is a widely used technique for establishing chronologies of lake-sediment cores. The ^{210}Pb analysis and reconstruction of historical sedimentation rates for the project was conducted by MyCore Scientific Limited. Details of the procedure used are presented by Evans and Rigler (1980), with modifications described by Cornett et al. (1984) and Rowan et al. (1994). ^{210}Pb is a naturally occurring radionuclide in the ^{238}U decay series. ^{210}Pb formed by *in situ* decay is termed the supported component and is in radioactive equilibrium with parent material. The ^{210}Pb activity in excess of the supported component is primarily derived by direct atmospheric fallout into the lake, which is scavenged by sediment particles and deposited on the bed of the lake. The unsupported component decays exponentially in time in accordance with its half-life (22.26 years). It is this predictable radioactive decay of excess ^{210}Pb that provides the basis for dating lake sediments. The concentrations of ^{210}Pb were interpreted using the constant rate of supply (CRS) dating model (Robbins 1978; Appleby and Oldfield 1978). This model is generally preferred over other interpretation techniques because it allows for fluctuating rates in sediment deposition over time. The CRS model assumes that the input of excess ^{210}Pb to the sediment-water interface has remained constant through time and that no post-depositional migration of the radionuclide has occurred over the dating interval. The total quantity of excess ^{210}Pb (calculated by numerical integration of the ^{210}Pb profile) is used in the determination of sediment ages and sediment accumulation rates.

Using the calculated age and rate of sediment accumulation for the core sections, profiles of historical lake-sedimentation rates at the sampling site can be developed. Sedimentation rates are best represented as horizontal lines plotted over core section intervals since the rate is an averaged measure across each section (several plots are included in this paper). Using this graphical representation, background lake-sedimentation rates were estimated. The background accumulation rate is assumed to be the component of the sediment load derived from primary denudation processes. Background sedimentation rates derived from ^{210}Pb dating can be multiplied by lake area to obtain an index of total sediment yield from the contributing lake catchment area. The assumptions of areal continuity (the measured sedimentary property should be deposited in similar proportions over the whole lake-bottom area) and synchroneity (once deposited, the measured property should be persistent and immobile) must be met for the calculated sediment yield to be a fair and consistent index of the actual sediment yield to the lake. The assumptions of continuity and synchroneity of lacustrine sediments are common in lake-sediment–based literature. Since cores were taken from the deepest point of the lake, the index will likely be an overestimate of actual yield because of sediment focusing effects in the lake basin. In lakes with a flat bottom and less sediment focusing, the sediment-yield index will approach the actual yield. In order to make lake-to-lake comparisons of catchment denudation rates, the sediment-yield index can be converted to a specific sediment yield, or sediment yield per unit of contributing basin area.

GIS Database Development

Due to the large volume of spatial data used in the project, ARC/INFO GIS technology was used to facilitate data management and queries. Several key existing databases have been used as basic inputs to the GIS for landscape-level spatial analysis. The two most important sources of digital data include the provincial terrain resource information management (TRIM) maps and the British Columbia Ministry of Forests forest cover mapping (FC1). Several other basic inputs were used to verify the lake inventory, such as: GPS-recorded, field-sampling locations; aerial photography; available historical maps (road maps, recreation maps, fishery reports, etc.); and personal communication updates from B.C. Ministry of Forests and B.C. Ministry of Environment personnel.

Two types of variables were extracted from the GIS database. The first set of variables are landscape indices, which are considered static over the time scale of this study. These indices consist of lake-catchment morphometric parameters that relate to the sediment production, conveyance, and storage for the basin. Primary landscape variables include: basin area, lake/wetland/valley areas, stream length, and elevation/slope statistics. The second set of variables are dynamic (time-dependent) land-use indices. These indices consist of planimetric parameters of land-use change within the lake catchment that could relate to anthropogenic modifications to sediment transfer. The land-use indices are calculated on a yearly basis since the time of the first land-use disturbance. Primary land-use indices include area logged and road length (with various slope and distance-to-stream modifiers). Analysis of the landscape data consisted of regression with tests of statistical significance, which are based on the assumption that variables are normally distributed. Variables describing natural landscape characteristics are often log-normally distributed. Based on visual examination of variable histograms, the log transformation was deemed necessary for all landscape indices except for lake elevation and drainage density.

Analysis of Sediment Records

The first step in investigating trends in the sediment records was to assess the natural patterns of lake sedimentation by relating the ^{210}Pb-derived sediment profiles to the landscape indices of the undisturbed lake catchments. This analysis was comprised primarily of standard linear regressions and analysis of variance. Secondly, the relative impact of land use on lake sedimentation was determined by relating the sediment profiles to temporal changes in the land-use indices for the disturbed lake catchments. This analysis was restricted to various semi-quantitative techniques, which are described in following sections. Based on these results, the usefulness of lake coring and associated analysis techniques as appropriate methods for determining long-term impacts of forest harvesting and other land-use disturbances on lacustrine sedimentation was assessed. Current knowledge of sediment transfer in British Columbia, and preliminary results in this study, suggest that sediment-delivery processes are strongly related to physiography and local geology. For this reason, most of the data set analyses were stratified for various physiographic units, as presented in the following section.

RESULTS PRESENTED BY PHYSIOGRAPHIC REGION

North Coast Region

Spectacular coastlines, steep-walled fjords, and rugged mountains characterize the region. Glaciated mountain peaks reach elevations in excess of 2000 m. Major rock-outcrop areas show fresh glacial landforms such as cirques, arêtes, and horns. Where bedrock is not exposed it is commonly thinly mantled by soil. Mean annual precipitation exceeds 2500 mm and in some areas surpasses 3500 mm. The North Coast study lakes were formed by glacial erosion in the mountains bordering the main valleys. They are medium-sized to large lakes with an elongated shape and very steep-sided bathymetry and immediate shoreline.

Background mid-lake sedimentation rates range from 49 to 2050 g/m^2/y. (Note: units of g/m^2/y are used to indicate rates of sedimentation per unit of lake basin area; units of t/km^2/y are used to indicate sediment yield per unit of the contributing catchment area.) The exceptionally high background sedimentation observed in some lakes reflects the large contributing drainage area, steep surrounding terrain, and close proximity to the Pacific Coast. Sedimentation rates in the North Coast lakes are highly variable over time. This reflects the episodic nature of sediment transfer in mountainous watersheds of British Columbia. The highest amount of variability is observed in lake catchments with an average slope greater than 30°. Possible land-use impacts could not be disentangled from the high degree of natural variability observed in this region.

Hazelton and Skeena Mountain Regions

The Hazelton and Skeena mountain ranges run north-south, parallel to the Coast Mountains. The Hazelton Mountains are bounded by the Kitsumkalum-Kitimat Trough to the west and the Kispiox and Bulkley rivers to the east. The Skeena Mountains are further inland between the Skeena and Bulkley rivers and the Nechako Plateau. Bedrock intrusions are not as widespread and relief is more moderate than that observed in the Coast Mountains. Some lake catchments contain high-alpine areas that remain snow-covered for most of the year. Precipitation is strongly controlled by orographic effects in this region. Mean annual precipitation ranges from over 3000 mm on the windward side of the Hazelton Mountains to about 500 mm on the leeward side of the Skeena Mountains. Pleistocene sediments impound all lakes in this region, although bedrock and active delta areas along the shorelines are not uncommon. Lake sizes and shapes are highly variable. Wetland areas are common in close proximity to the study lakes.

Background mid-lake sedimentation rates range from 40 to 600 $g/m^2/y$, largely controlled by the size of the contributing area. As observed in the Coast Mountains, episodic events dominate sediment transfer in many of the lake catchments. Elevated rates of lake sedimentation following land-use disturbances have been observed in most catchments, up to double the observed background levels. There is no obvious pattern between the degree of disturbance and the magnitude of the sedimentation increase. In most cases, sedimentation rates had been increasing before the onset of the land-use disturbances. Furthermore, about half of the control lakes also show a consistent increasing trend in mid-lake sedimentation rates beginning around 1950. This natural trend of increasing sedimentation over the last half of the century confounds the land-use signal, so the degree to which forestry activities have influenced downstream sedimentation is undetermined.

An interesting lake-sediment signature was observed in Aldrich Lake, located about 12 km west of Smithers on the opposite side of the Hudson Bay Range. A watershed map and sedimentation rate profile with the timing of land-use development in the catchment are included in Figure 2. Road and mine development began north of Aldrich Lake in the early 1920s. Production was intermittent between 1930 and 1940, but by 1950 the mine operated at its highest production rates. The final year of operation was 1954. Mid-lake sedimentation rates in Aldrich Lake increased steadily from a background rate of about 300 $g/m^2/y$ to close to 700 $g/m^2/y$ during mine operation. Sedimentation rates reached their highest levels of 780 $g/m^2/y$ in the decade following mine production. This peak in sedimentation was likely associated with road failures and a blowout that occurred in the old tailings dump. Sedimentation rates dropped in the following years, but then again started to increase when forestry activities began in 1984.

Nass Basin and Major Valleys Region

Areas classified in this region include low-lying depressions and large valley flats located between major mountain ranges. The Nass Basin and the Skeena, Bulkley, and Kispiox valleys comprise most of this area. Rivers presently occupy these regions, but during Pleistocene glaciation they served as channels down which glacier ice moved. The region contains hummocky, rolling, and undulating terrain underlain by thick Quaternary sediments. The broad valley bottoms range from 200 to 500 m in elevation and have gentle relief. Climate ranges from the maritime environment of the coast to the continental climate of the interior. Most of this region is road-accessible and has been subject to timber-harvesting activities. The lakes in this region are relatively small compared to those in the other study regions. The lakes located in the major valleys are impounded by thick Pleistocene deposits. Lakes in the Nass Basin occupy low plateaus in a series of glacially scoured troughs running northwest-southeast. Wetlands and low-lying swampy areas are also common around the lakes. Distal to the lakes are high-relief mountainous areas.

Background mid-lake sedimentation rates range from 16 to 186 $g/m^2/y$. Lakes with larger contributing areas generally have higher sediment-loading rates, although sedimentation rates are not well predicted by any linear

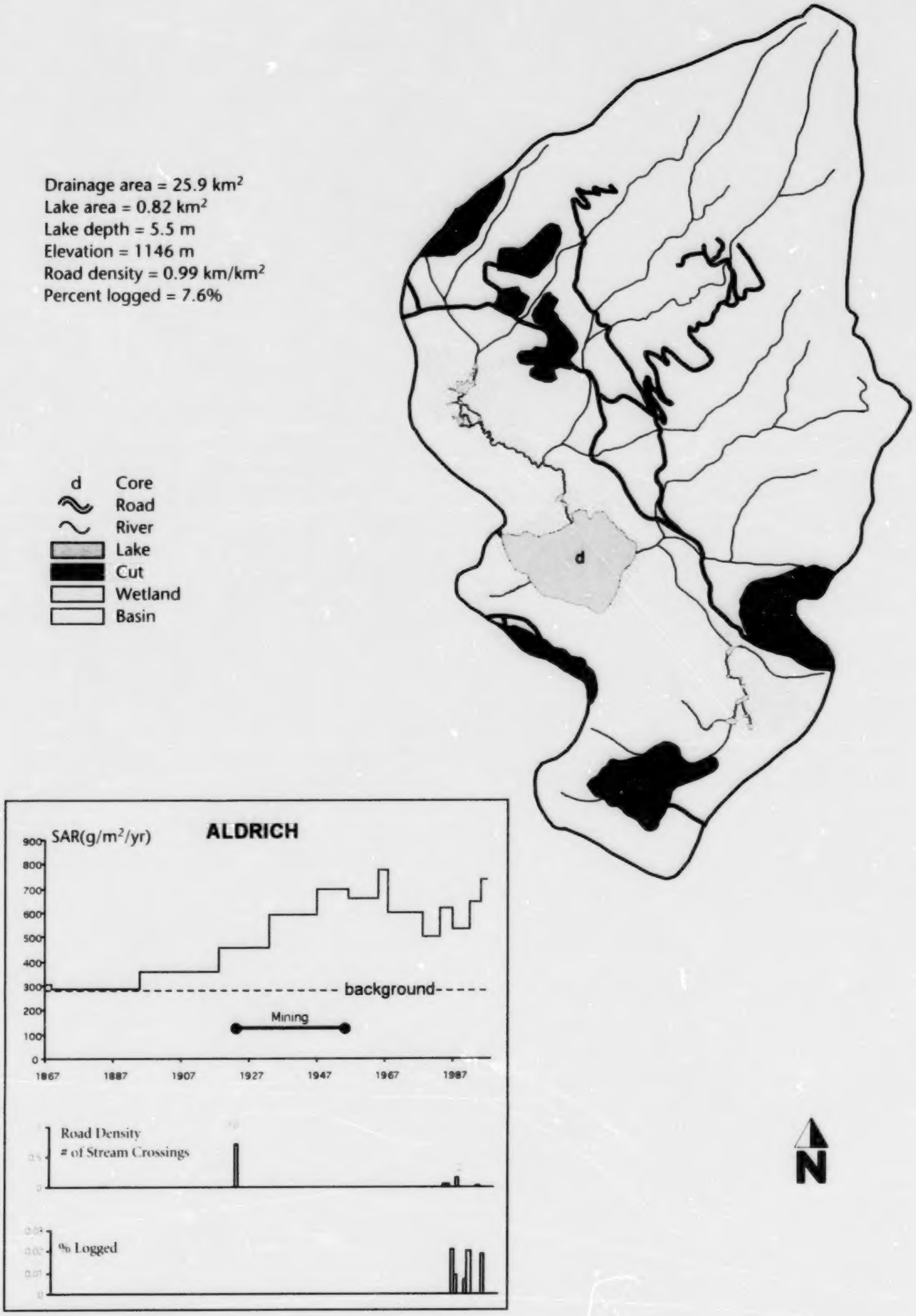


FIGURE 2 *Aldrich Lake.* SAR *is sediment accumulation rate in g/m²/y, road density is given in km/km², and amount logged is given as a ratio to drainage basin area.*

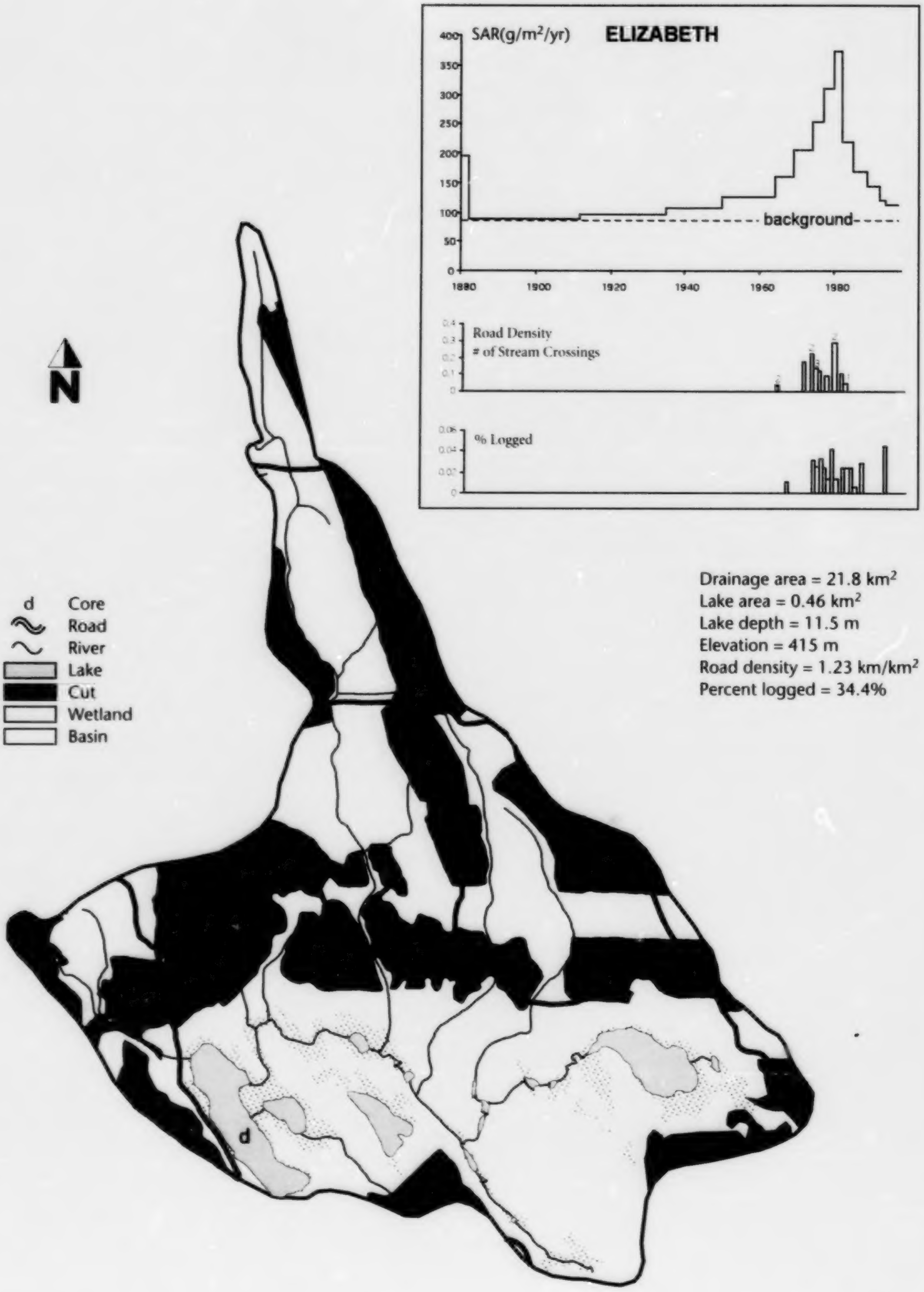
combination of landscape variables. Half of the control lakes show an increasing trend in sedimentation in the latter half of their sediment records (50–100 years), a similar trend to that observed in the Hazelton/Skeena region lakes. Most disturbed lakes have experienced an increase in sedimentation coinciding with road construction and timber harvest. The lakes with the highest number of stream crossings had the greatest increases in sedimentation. Although almost all lakes have higher sedimentation rates following the forestry activities, several of the control lakes in the region show a similar trend in recent accumulation rates.

Elizabeth Lake is the only lake that clearly shows a recovery of sedimentation rates following completion of land-use disturbances back to background levels. A map of the lake catchment and a plot of sedimentation rates and land-use history of Elizabeth Lake are shown in Figure 3. Notice that sedimentation rates begin to increase immediately following the initial road construction in the lake catchment. Sedimentation rates continued to rise while road construction continued and logging began north of the lake. The highest sedimentation rate of 374 g/m^2/y (307% above background) occurred 2 years following the most major road construction and significant logging in the catchment in 1980. Sedimentation rates began to recover when road construction in the basin was completed. Some timber-harvesting activities continued through the falling limb of sedimentation.

Nechako Plateau Region

The Nechako Plateau is the only extensive plateau region in northwestern British Columbia. The Bulkley River extends southeastward into the Nechako Plateau, a rolling region with elevations ranging from 800 to 1200 m. The Nechako Plateau is bordered on the west by the Hazelton Mountains and to the north by the Skeena Mountains. The Nechako Plateau makes up part of the Interior Plateau region of British Columbia. The climate of Nechako Plateau is continental, and is characterized by seasonal extremes of temperature and moderate annual precipitation. This region contains the least dramatic relief of all of the study areas. Flat-lying volcanic strata and glacial drift overlie older bedrock in this region. Rivers flow in deep, glacially modified valleys cut into the rolling uplands. Lakes and wetlands dot the landscape in poorly drained, post-glacial depressions. Most of this region is road-accessible and has been subject to timber-harvesting activities. The largest range of lake and lake-catchment sizes is found in this region. Lake basins are fairly regular in shape and are relatively shallow compared to the lakes in the other study areas. Low-lying and poorly drained peat bogs, marshes, and swamp areas are common. Small lakes and ponds are abundant in the study catchments, many being held behind old beaver dams. There are no signs of hillslope coupling in the relatively flat terrain of this region.

Background mid-lake sedimentation rates range from 30 to 280 g/m^2/y. As observed in the other regions, lakes with a larger contributing area generally have higher sediment-loading rates. However, similar to the Nass Basin and Major Valleys region, background sedimentation rates are not well predicted by any linear combination of landscape variables. Lakes in the Nechako region show similar patterns of sedimentation as observed in the Nass Basin and Major Valleys. Half of the control lakes have had increasing sedimentation rates over the last several decades. This natural increase in sedimentation rates has been observed in about half of the control lakes in this study, making interpretation of the effects of land use on the sediment signatures significantly more difficult because the timing of this increasing



Drainage area = 21.8 km^2
Lake area = 0.46 km^2
Lake depth = 11.5 m
Elevation = 415 m
Road density = 1.23 km/km^2
Percent logged = 34.4%

FIGURE 3 *Elizabeth Lake.*

trend coincides closely with land-use impacts. Again, all but a couple of the lakes that have experienced forestry-related, land-use disturbances have coinciding increases in their sedimentation rates. Catchments with greater land-use disturbances generally show greater increases in sedimentation, but this relation does not hold for all lakes.

Takysie Lake is a large lake located well within the Nechako Plateau in the southeast corner of the study area. The Takysie catchment has been subject to a long and diverse land-use history. The lake catchment and sediment profile are included in Figure 4. Sedimentation rates in Takysie Lake have been increasing since 1865, the earliest date available from the ^{210}Pb analysis. Most of the increase has occurred following road construction, timber harvest, and other land-use activities, including animal grazing, agriculture, residential development, and resorts/camping. The time of first land-use disturbance is unknown, but most development is known to have occurred since 1930, primarily to the west of the lake. The sediment profile does not reach a level background rate. ^{210}Pb analysis done in a paleolimnological assessment of Takysie Lake by Reavie and Smol (1998) indicated a background sedimentation rate of about 30 g/m^2/y. This background rate fits the trend observed early in our sediment record. Both results showed a similar increase in sedimentation rates over the latter part of the century. Our results gave a higher peak-sedimentation rate of 269 g/m^2/y compared to about 210 g/m^2/y in their study. Sedimentation rates have increased 600–800% above background in Takysie Lake over the last 150 years. Not all of this increase can be linked to land use because rates were increasing before land-use activities began in the catchment. However, an increase of this magnitude is unprecedented for the lakes in this study. Reavie and Smol (1998) attributed the increasing sedimentation rates to lake eutrophication caused by elevated nutrient input from human development surrounding the lake.

REGIONAL PATTERNS OF LACUSTRINE SEDIMENTATION

Within-lake Variability

A minimum of four cores were sampled from the deepest point of the central basin of each lake. Whenever possible, additional cores were taken at points located elsewhere in the lake basin. A visual comparison was made in the field between all the cores taken from each lake. If the sediment cores contained visual markers (event layers, varving, change in sediment character, etc.), then the assumptions of areal continuity and synchroneity of the lake sediments could be verified. Lake sediments must have these properties for cores to be representative of deposition across the entire lake. If the assumptions of areal continuity and synchroneity are valid, sediment properties in order will be consistent and sediment will be deposited in similar proportions over the whole lake area. Cores from the same lake should then all have a similar and consistent sediment structure. There were no cases where the assumptions of areal continuity and synchroneity of lake sediment did not appear to be valid for mid-lake areas. The focusing of sediment to deeper lake areas was evident because the distance between horizons in the sediment cores usually decreased as cores were sampled in shallower water. In lakes with a relatively flat bottom, the distance between horizons would increase as cores were sampled closer to the main inflow to the lake. The deepest spot in these lakes would not have been the optimal sampling location for obtaining the best temporal resolution in the lake-sediment analysis. Cores taken in

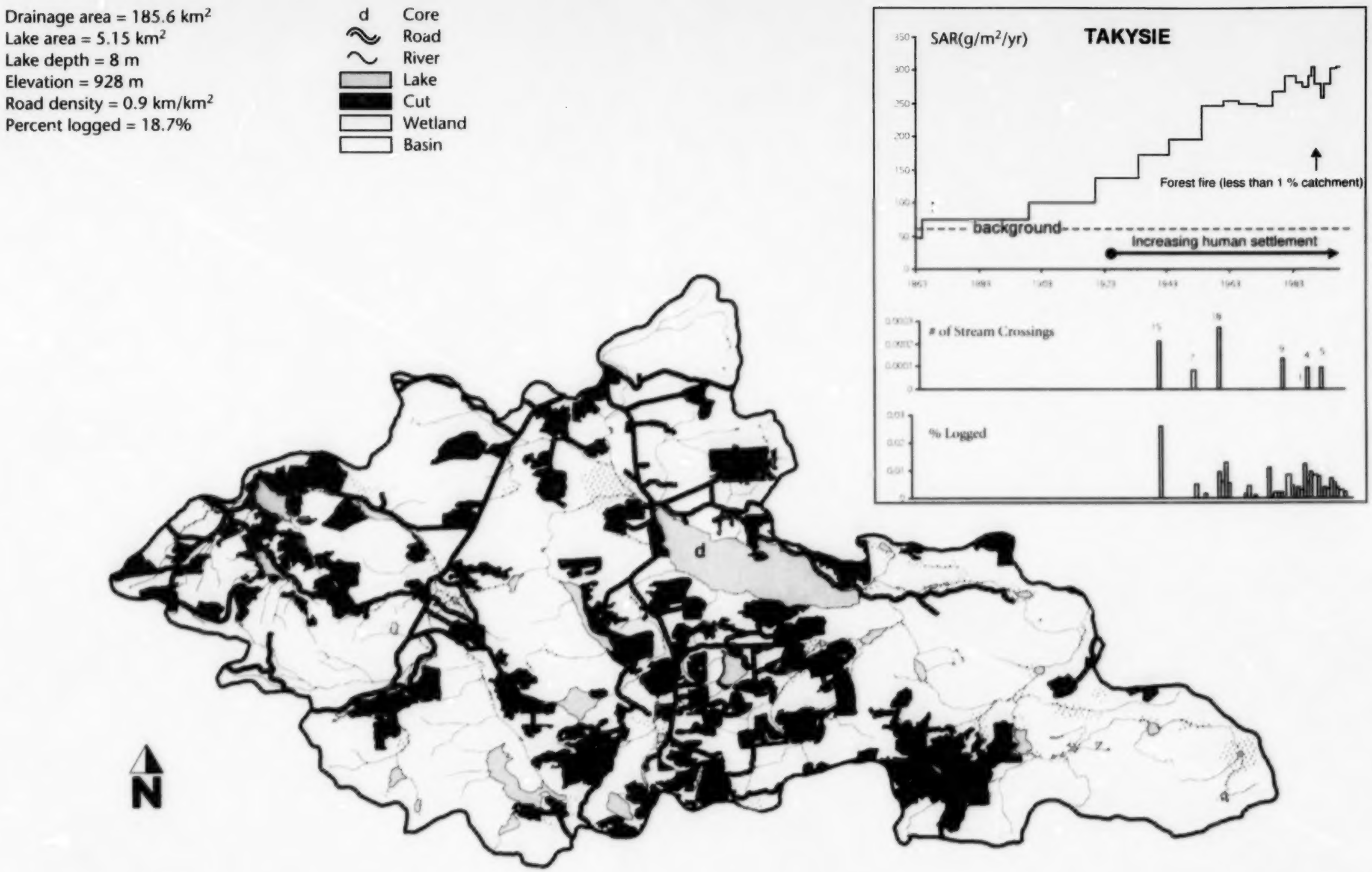


FIGURE 4 *Takysie Lake.*

shallower water and from near-shore locations would not always have a stratigraphy similar to that of the mid-lake cores. This was especially true in cores that were sampled on steep, lake-bottom slopes, above the lake thermocline, or on a delta front. These sediments are subject to re-suspension and transport by sub-aqueous slumping, water currents, and wind/wave action. Lakes best suited for this study have a well-defined and deep central basin, with a relatively flat bottom that is out of the influence of deltaic and near-shore processes. Lakes were selected that appeared to best meet these requirements in order to help assure areal continuity and synchroneity of the lake sediments. This was reflected in the high degree of correlation between mid-lake sediment cores.

Seven of the study lakes had varving over a segment of their sediment cores. All the varved sediments were from North Coast lakes or from lakes in the northern portion of the study area. This suggests that the presence of glaciers and strongly contrasting summer and winter hydrologic conditions are important factors in the development of varving. All the lakes were strongly stratified at the time of sampling and had good sediment-focusing characteristics. A comparison of averaged sedimentation rates derived from ^{210}Pb dating and annual varve counting is provided in Table 1. There is a high degree of correlation between the averaged sedimentation rates calculated using both methods. The ^{210}Pb calculated rates are slightly greater in six of the seven lakes. This bias may indicate a minor error in the estimation of the background ^{210}Pb concentrations used in the sediment accumulation-rate calculations. Nevertheless, the high agreement between the relative and absolute chronologies improves our confidence in the dating techniques used.

Regional Variability

Background sediment yield is a measure of the volume of sediment being deposited in the lake basins. Investigating relations between the sediment yield and landscape characteristics of the contributing basin is useful for developing predictive equations for estimating sediment yield in the general study area. This can be done using easily obtainable drainage basin parameters, thus avoiding costly field-sampling programs. Although this type of empirical analysis does not prove any cause-and-effect relations between sediment yield and landscape characteristics, these non-causal relationships may

TABLE 1 *Comparison of sedimentation rates calculated from ^{210}Pb dating and varve counting*

Study lake	Core segment (cm)	Averaged estimated sedimentation rate (g/m^2/yr)	
		^{210}Pb dating	Varve counting
Toon	1–19	418	412
Amoth	14–30	2723	2533
Unnamed KM1	18–20	204	180
Jade	8–9	1075	1050
Alpha	6–12	60	76
Dragon	4–6	470	400
Mitten	2–4	147	135

represent important prologues to further theoretical understanding of the underlying physical processes of sediment transfer. A stepwise linear regression was performed with background sediment yield estimated from the ^{210}Pb dating of the sediment cores (dependent variable) and all the GIS-derived landscape indices for the lake inventory (independent variables). The regression was run for each physiographic region and for the entire data set. The regression results, including the ANOVA of the regressions, are presented in Table 2.

All of the regression line slopes are highly significant (P = 0.001). In all cases the drainage basin area is the most important predictor variable. Sediment yield in the North Coast region is well predicted by the contributing drainage-basin area. Total valley-flat area and drainage density were important variables in the Hazelton and Skeena mountain regions, respectively. Valley-flat area is a term describing storage potential in the catchment. Valley-flat area is defined as the sum of continuous, flat-lying (less than 1° slopes) land and water-body (upstream wetlands and lakes, excluding the study lake) areas in valley-bottom areas of the lake catchment. These are areas where net accumulation of sediment occurs. Therefore, catchments with large valley-flat areas are more likely to have lower sediment yields, hence the negative influence on yield in the Hazelton Mountains. Conversely, drainage density had a positive influence on yield in the Skeena Mountains as a term that describes the transport capacity of a catchment. Since fine sediment is transported in suspension through stream channels, catchments with greater stream lengths per unit area will more efficiently transfer mobilized sediment from the land surface, through the stream network, to the receiving lake downstream. Sediment yields in the Nass Basin and Major Valleys region and in the Nechako Plateau region are not well predicted by any linear combination of the landscape indices. With the complete data set, drainage-basin area and mean slope of the catchment were the most significant predictor variables. It is not surprising that slope emerged as a significant variable in the all-regions regression. Average slope of a catchment relates to both storage

TABLE 2 *Background sediment yield regression and ANOVA results*

North Coast $\log(Y) = 0.76 + 1.38\log(A_b)$ $n = 9, R^2 = 0.86$ F Value: $\log(A_b) \rightarrow 43.5^{***}$	**Nass Basin and Major Valleys** $\log(Y) = 1.09 + 0.51\log(A_b)$ $n = 18, R^2 = 0.46$ F Value: $\log(A_b) \rightarrow 13.7^{**}$
Hazelton Mountains $\log(Y) = 0.19 + 1.43\log(A_b) - 0.66\log(VFA)$ $n = 16, R^2 = 0.83$ F Values: $\log(A_b) \rightarrow 50.7^{***}$, $\log(VFA) \rightarrow 11.2^{**}$	**Nechako Plateau** $\log(Y) = 1.42 + 0.43\log(A_b)$ $n = 21, R^2 = 0.47$ F Value: $\log(A_b) \rightarrow 16.6^{***}$
Skeena Mountains $\log(Y) = 1.12 + 1.84\log(A_b) + 0.62DD$ $n = 12, R^2 = 0.84$ F Values: $\log(A_b) \rightarrow 39.3^{***}$, $DD \rightarrow 8.3^{*}$	**All Regions** $\log(Y) = 0.59 + 0.77\log(A_b) + 0.52\log(slope)$ $n = 76, R^2 = 0.66$ F Values: $\log(A_b) \rightarrow 134.1^{***}$, $\log(slope) \rightarrow 8.0^{**}$

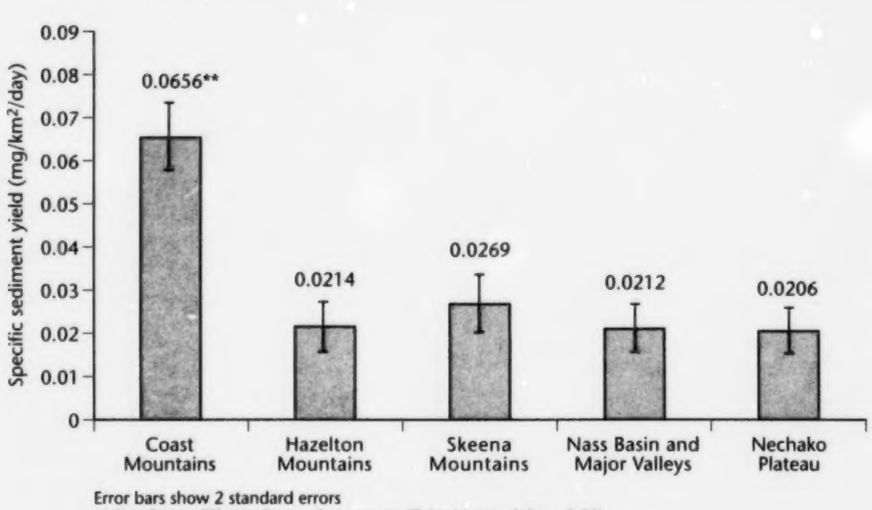
Where: Y is the background sediment yield (Mg/y)
A_b is the area of the drainage basin (km^2)
VFA is the total valley flat area upstream of lake including water bodies (km^2)
DD is the drainage density (km/km^2)
Slope is the mean slope of the land surface area (degrees)

* $P < 0.05$
** $P < 0.01$
*** $P < 0.001$

potential (negatively—sediment accumulation is more likely in flat-lying terrain) and transport capacity (positively—steep terrain is more likely the source or transport area of sediment) of the basin. It is unclear if the regression results for all regions combined makes sense when the regional component regressions yield different results, which implies the possibility of different underlying physical processes in the different regions. It is interesting to note that the R^2 values are the highest in the mountainous areas (North Coast, Hazelton Mountains, and Skeena Mountains). The greater storage potential of sediment in the flatter catchment areas (Nechako Plateau, Nass Basin, and Major Valleys) may be confounding the predictability of sediment yield.

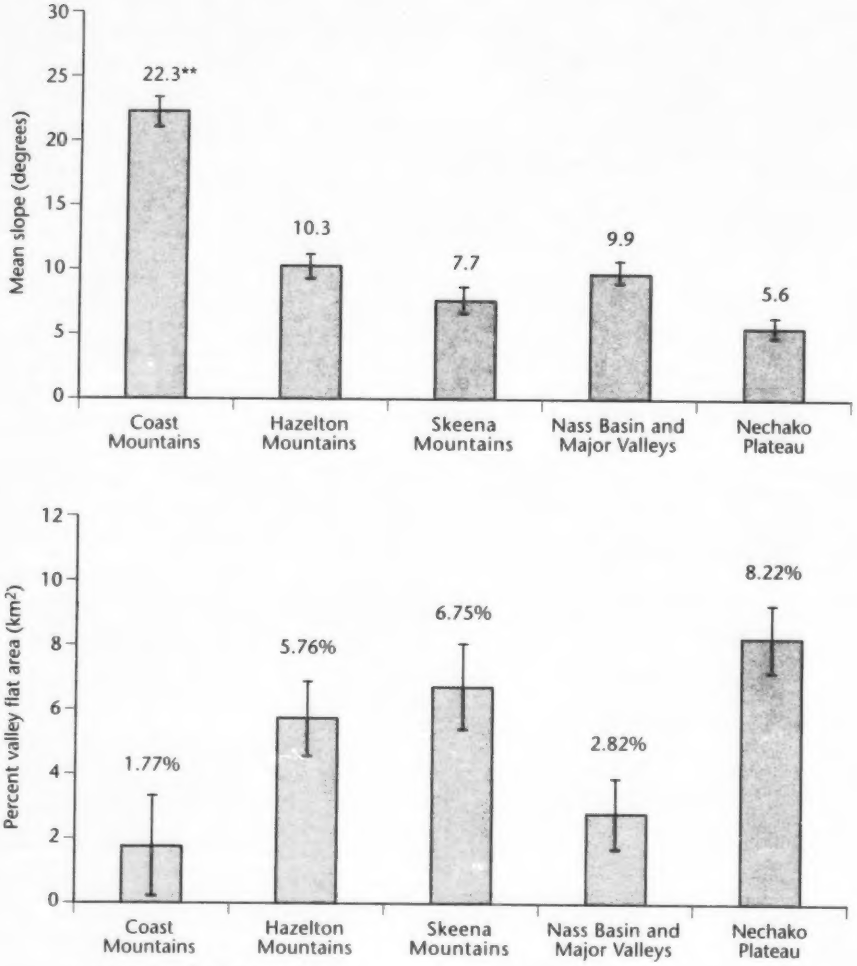
Specific sediment yield, or sediment yield per unit of contributing basin area, is used as an index of primary subareal denudation of the lake catchments. Lake-to-lake and regional comparisons in catchment denudation rates can be made using specific yield, since it accounts for basin scale and areal focusing of sediment into the receiving lake. Specific yield ranges from 0.55 t/km^2/y in the interior, to 52 t/km^2/y in the Coast Mountains. The average specific yield over all the lake catchments is 10 t/m^2/y. The average specific yields for the different physiographic regions are plotted in Figure 5. ANOVA indicated a statistical difference in the regional specific yield means. Using Tukey's test (alpha = 0.01), the North Coast region was shown to have a statistically greater mean specific yield compared to the other regions. The higher rate of sediment yield per unit area in the North Coast reflects the higher erosion rates due to the greater transport capacity and lower storage potential in that region. These characteristics of the North Coast region are reflected in the landscape variables of mean slope and valley-flat area shown in Figure 6. The North Coast lake catchments have significantly steeper slopes and less valley-flat area than the other study regions.

In British Columbia, using suspended-sediment-load data obtained by the Water Survey of Canada, Church and Slaymaker (1989) observed a pattern of increasing specific sediment yield at all spatial scales up to 3 × 10^4 km^2. This trend results from the dominance of secondary remobilization of Quaternary sediments from streambanks and valley-bottom areas over primary



Error bars show 2 standard errors
** Significant different from other groups (Tukey's test, alpha = 0.01)

FIGURE 5 *Regional differences in specific sediment yield.*

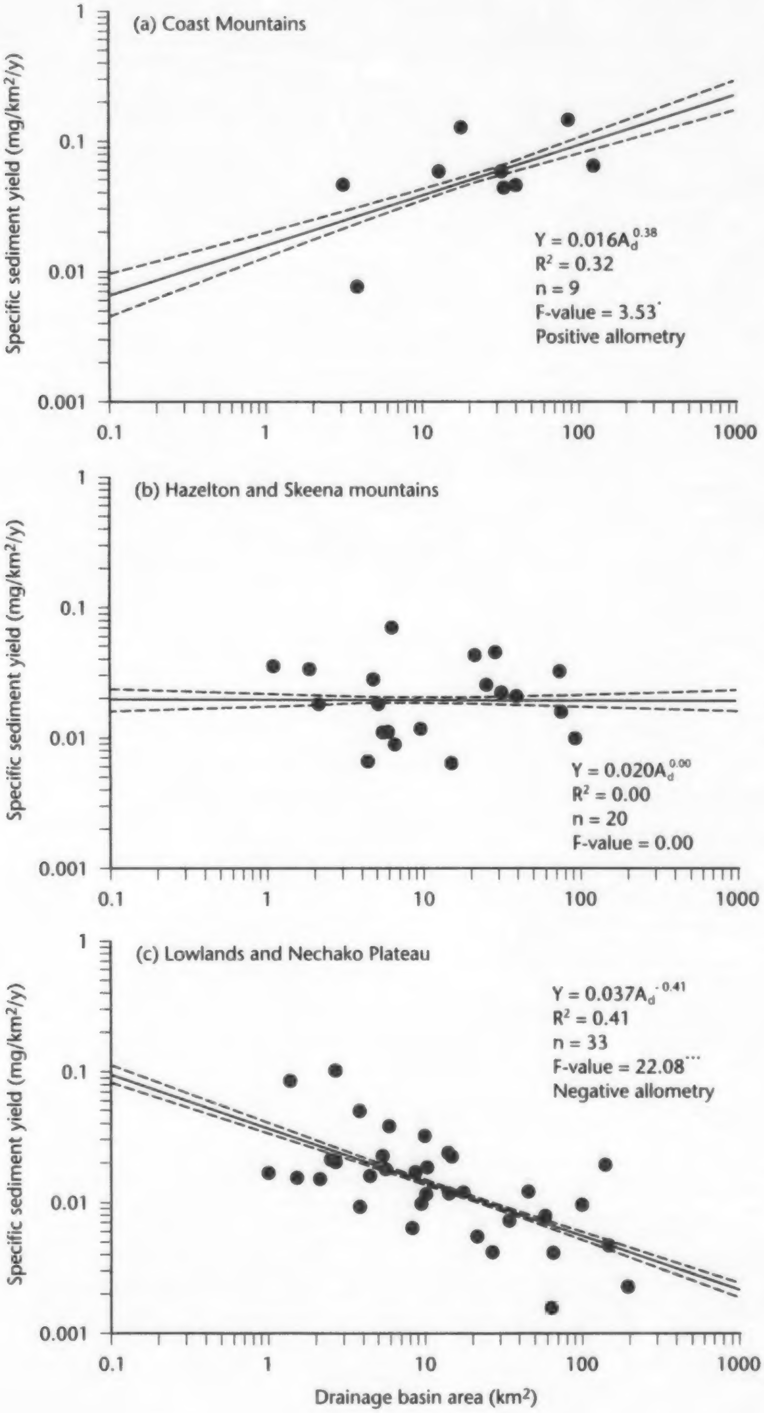


Error bars show 2 standard errors
** Significant different from other groups (Tukey's test, alpha = 0.01)

FIGURE 6 *Regional differences in mean slope and valley-flat area of study catchments.*

denudation of the land surface. This result indicates that sediment yield of larger drainage basins remains conditioned by the extraordinary glacial events of the Quaternary Period, where large quantities of unconsolidated sediments were delivered to the major valleys of British Columbia (Church and Ryder 1972). This pattern controverts the conventional model of specific sediment yield, in which increased sediment storage downstream dominates sediment-transfer processes. As drainage area increases, a greater proportion of the mobilized sediment load is supposed to become trapped in the downstream cascade of storage zones on footslopes, floodplains, and in low-energy water bodies such as lakes and wetlands. There is no specific yield–drainage area relation in the lake-sediment–derived data as a whole. However, some interesting patterns emerge when the data are stratified physiographically, as shown in Figure 7.

Plot A in Figure 7 shows spatial trends in specific yield for the North Coast study catchments. These are high-energy systems that contain very steep terrain and receive large amounts of precipitation. Upland slopes are thinly



Notes - Catchments from transitional areas have been removed (10 catchments dropped)
- Dashed lines are 95% confidence intervals of fit
- Significance of F statistic: $^{*}\ p < 10^{-1}$, $^{**}\ p < 10^{-2}$, $^{***}\ p < 10^{-3}$

FIGURE 7 *Specific sediment yield as a function of drainage area.*

mantled, with large areas of exposed bedrock. Storage potential is low, since there is relatively little flat terrain in the contributing catchments of the lakes. Sediment yield increases with drainage area for lake catchments in this region. Sediment yield is roughly proportional to (drainage area)$^{0.4}$. This fits the Church and Slaymaker (1989) model of sediment yield where remobilization of Quaternary sediment dominates sediment transfer in the basin. Pleistocene deposits on lower valley slopes (fans and aprons) and valley-bottom areas are likely the predominant sediment sources for lakes in the North Coast region. Plot C in Figure 7 shows spatial trends in specific yield for the Nechako Plateau, Nass Basin, and Major Valley study catchments. These are much lower energy systems with gentle relief and a drier continental climate. Upland slopes are mantled by thick glacial deposits. Lakes, wetlands, and broad valley-flat areas are common upstream of the study lakes. Storage potential is, therefore, quite high in these areas. Sediment yield decreases with drainage area for lake catchments in these regions. Sediment yield is roughly proportional to (drainage area)$^{-0.4}$. This trend fits the conventional model of sediment yield where sediment mobilized from upland areas goes back into storage on footslopes, floodplains, and water bodies further downstream. Plot B in Figure 7 shows the spatial yield pattern for the Skeena and Hazelton mountain study catchments. The landscape characteristics of this region are intermediate to the regions discussed above. No scale-related trend in yield was detected in these catchments; in other words, specific yield is in a state of constant proportion with drainage area. This pattern of specific sediment yield does not clearly fit either of the two models mentioned previously. In all regions the range of specific sediment yield spans an order of magnitude at all spatial scales, likely the consequence of local geology. The reader is directed to Schiefer (in press) for a more detailed discussion of physiographic controls on sediment yield in British Columbia.

Temporal Variability

Sediment transfer in headwater catchments of British Columbia is commonly dominated by large-scale episodic events, in which large volumes of sediment are flushed through the system over relatively short periods of time. These high-magnitude/low-frequency events include processes such as mass wasting, streambank failures, and breaking of log jams. In the case of lake sedimentation, autochthonous processes could also be the cause of large fluctuations in sedimentation rates, including physical and biological events such as turbidity currents off a slumping delta front, or changes in lake productivity. The analysis of these disturbances is restricted because the sampling techniques lack the temporal resolution to properly capture these events, especially if they occur early in the sediment records. Another problem in dealing with these low-frequency disturbances is that the sedimentary records are too short to address the overall importance of these events in drainage basin sediment transfer.

Over a third of the study lakes had a significant peak (any recorded sedimentation rate approximately 100% or greater above the estimated background rate) in their sedimentation-rate profile without the influence of any land-use activities occurring in the basin. While these peaks in the sedimentation rates may be indicators of significant natural disturbances in the lake catchment, the specific causes of these fluctuations are unknown. These occurrences are most common in the mountainous regions, although they are observed in all regions. A closer look at the sediment profile of Shea Lake, a lake with a well-captured disturbance event, is made in Figure 8. Over a 19-year period (1929–1948), sedimentation rates in Shea Lake increased to a

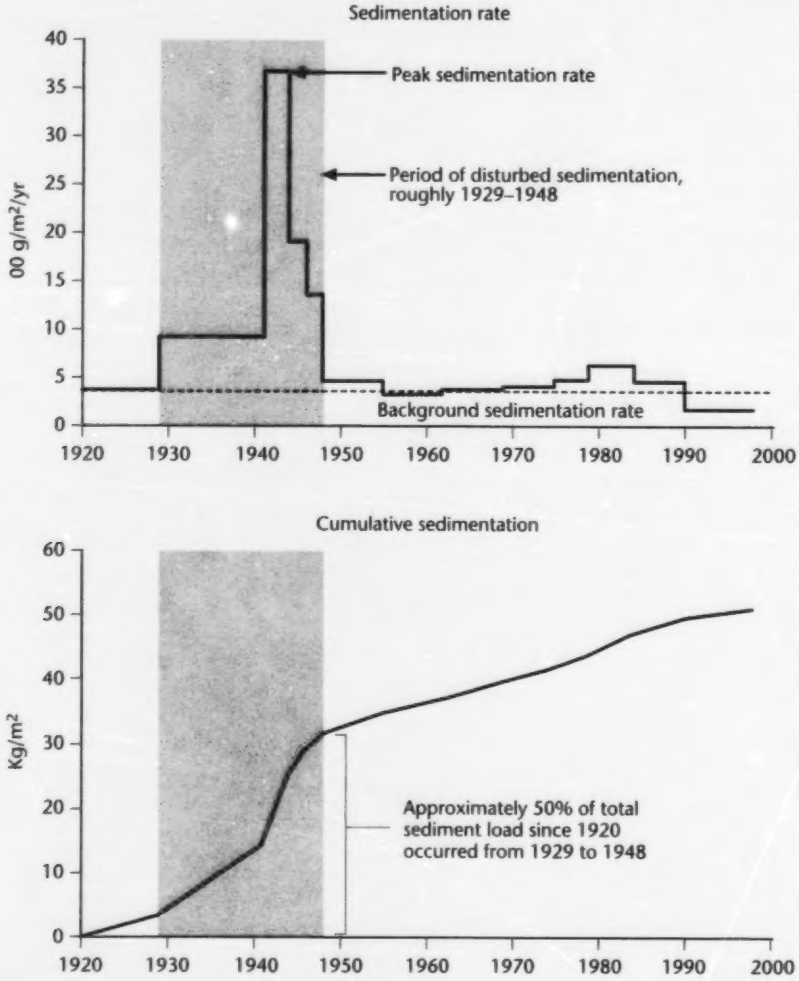


FIGURE 8 *Disturbance event in Shea Lake profile.*

peak rate 10 times greater than background. During that time about half of the total sediment load since 1920 was deposited in the lake basin.

Many of the sediment records show a significant increase in lake-sedimentation rates over the latter half of the century. This trend has been observed in all study regions. Of the control lakes, 11 of 23 clearly show this increasing trend in sedimentation rates, with increases ranging from 30 to 167% above background levels. Some lake catchments that have had land-use disturbances show the same increasing trend beginning before the onset of land use in the catchment. On average, sedimentation rates have been increasing irrespective of land-use change in the study lakes for the last 50 years. This could be a response to climatic change in the region. A relationship between sedimentation rates and precipitation would be expected, since the hydrologic cycle is the major driving force in sediment transfer. To investigate this possibility, precipitation records for the region (Prince Rupert, 89-year record; Terrace, 85-year record; and Smithers, 55-year record) have been analyzed. Cumulative departure plots were used to identify periods of above- and below-normal annual precipitation (Figure 9). An increasing

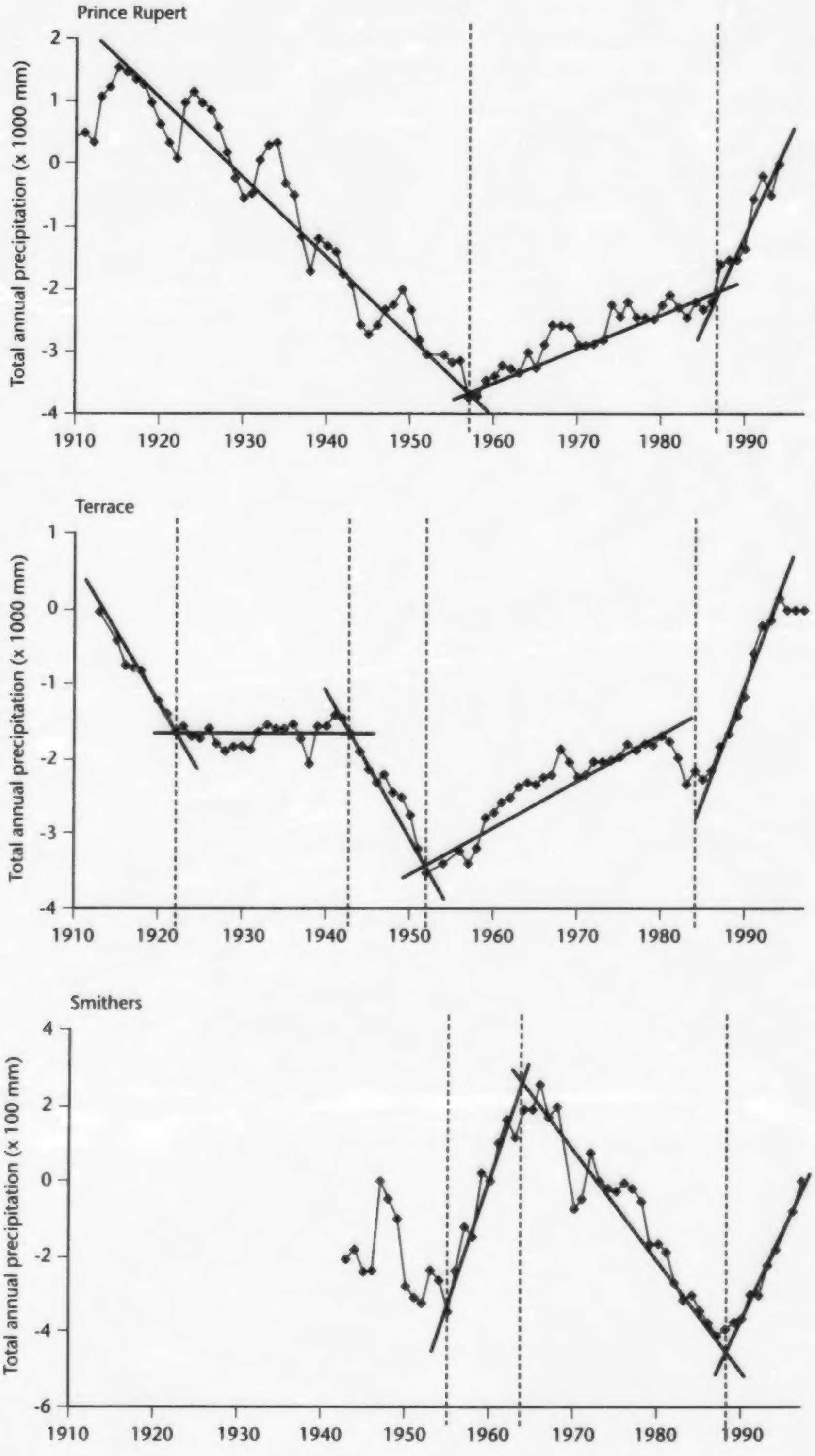


FIGURE 9 *Cumulative departure plots for Skeena region precipitation.*

trend in sedimentation rates would be expected to coincide with above-average periods of precipitation. The plots for Prince Rupert and Terrace show a similar pattern of below-average or average precipitation for the first half of the century followed by above-average precipitation. Both locations have also experienced precipitation significantly above normal for the last 20 years. Smithers, which is located in the interior portion of the study area, shows a different pattern in annual precipitation: rates have been above normal for the periods 1955–1965 and 1987–present, with an intervening period of below-normal precipitation between 1965 and 1987. These plots show that precipitation has been above average in the coastal areas for the last 50 years, and considerably above average over the entire region for the last 15–20 years. This indicates that the increasing trend in sedimentation rates may be, at least partially, a consequence of climatic trends in northwestern British Columbia. Storm-frequency analysis has not been carried out on the precipitation records. Since peak runoff events are often the result of the combination of complex hydro-climatic processes (including cyclonic storms, spring snowmelt, and rain-on-snow events), stream discharge records could be more useful in studying the occurrence of important sediment-transporting flood events. Unfortunately, few long-term discharge records are available in the study area, especially in headwater drainage basins.

Impacts of Land Use

The majority of lake catchments in this study have been subject to road construction and timber-harvesting activities. Most of these activities have occurred in the last couple of decades. In most cases a significant increase in mid-lake sedimentation rates has coincided with these land-use disturbances. However, since about half of the control lakes have also had an increase in sedimentation rates over the last few decades, the extent to which forestry has affected lake sedimentation is uncertain. Of the lakes in the control set, 48% (11 of 24) have had a recent increase in sedimentation rates. The average increase was 90% above background rates, with a maximum observed increase of 167%. For lakes that have been subject to road construction and timber harvesting, 84% (32 of 38) have had increasing sedimentation rates. The average increase was 137% above background rates, with a maximum observed increase of 307%. The largest recent increases in sedimentation rates have occurred in lakes of the Nechako Plateau and the Nass Basin and Major Valleys regions. These are the regions that have also experienced the greatest amount of forestry activity because of their less-rugged terrain and greater accessibility. Overall, lakes that have had road construction and timber harvesting in their watersheds have experienced greater increases in mid-lake sedimentation rates than the control lakes. In addition to forestry, other major land-use disturbances have occurred in two of the study catchments. A mining operation was active north of Aldrich Lake from the early 1920s to 1954. Human settlement began west of Takysie Lake early in the century and was followed by ranching, agriculture, residential development, and resort/camping activities. The sediment records for both Aldrich and Takysie lakes show significant increases in sedimentation over the duration of these land-use disturbances. Although sedimentation-rate increases coinciding with land-use disturbances are easily identified, they are well below the maximum relative increases observed, which are likely associated with natural geomorphic events.

The recent natural trend of increasing sedimentation rates observed in about half of the control lakes is a major confounding effect in the interpretation of land-use signals in the sedimentary record. To separate, to some extent, this trend and natural episodic events from the sedimentation rate profiles, the graphs in Figure 10 were developed. The first graph plots the departure of sedimentation rates from background levels for control lakes using smoothed lines with large peaks filtered out. The remaining profiles of control lakes were used to define an envelope of naturally occurring sedimentation rates. The wedge-shaped envelope clearly shows the increasing trend in sedimentation rates observed in many of the control lakes over the last 50 years. Beyond the envelope limits are regions defined as having unusually high and low sediment-accumulation rates. The second graph shows

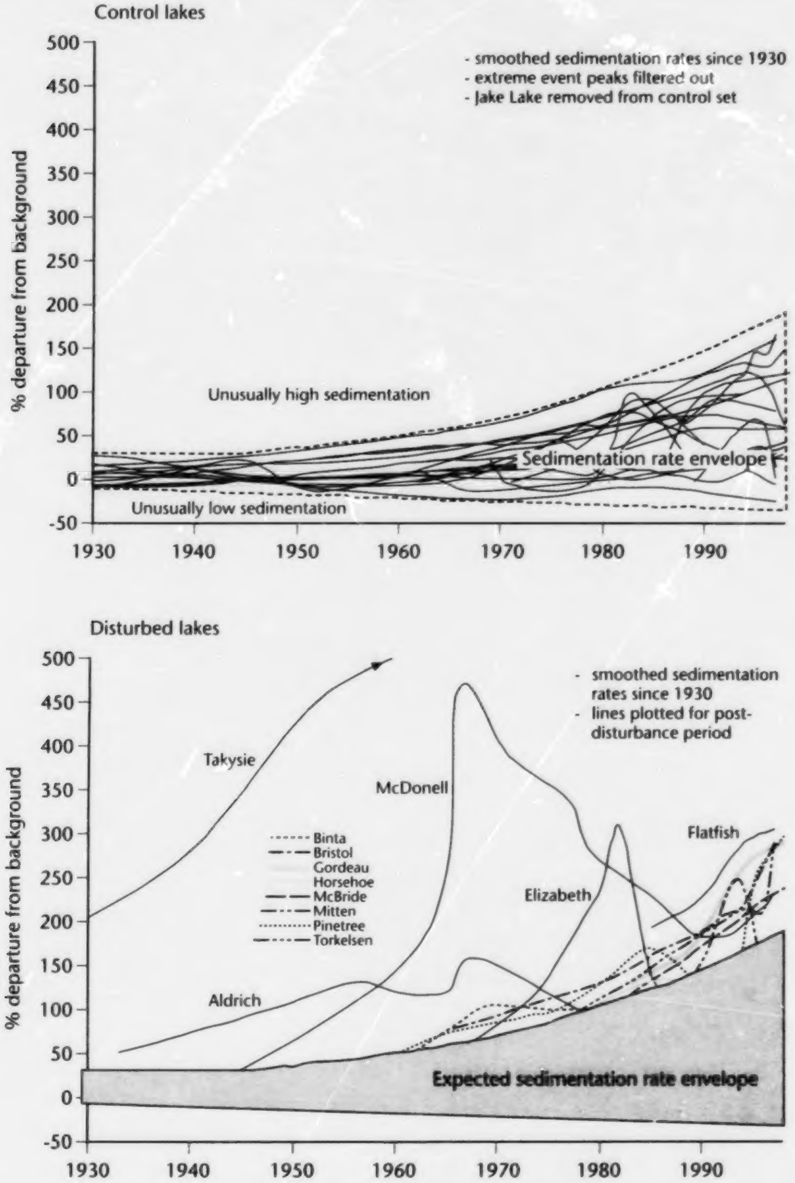


FIGURE 10 *Separating land-use impacts from natural variability.*

the departure from background sedimentation for lakes that have had land-use disturbances in their contributing catchment areas. No disturbed lakes plotted below the lower envelope limit. Thirteen lakes were identified as having unusually high sedimentation rates because they plotted above the upper envelope limit. These unexpectedly high sedimentation rates are likely related, at least partially, to land-use disturbances in the lake catchments. Most of these lake catchments are relatively small and have been heavily logged (generally over 20%) and roaded (generally over 1 km/km^2) with some harvesting activities located immediately adjacent to the lake and contributing stream channels. This is a reasonable expectation—small watershed areas with extensive land-use coupled to the hydrologic network are the most sensitive to disturbance, although it should be noted that there were some catchments fitting these criteria that did not experience an unusually high sedimentation response.

CONCLUSIONS AND FUTURE WORK

Lake-sediment sampling and analysis has been utilized to investigate historical lacustrine sedimentation patterns in northwestern British Columbia. Seventy lake catchments were selected for study that span a range of spatial scales, physiographic regions, and land-use histories, in order to permit a comprehensive regional assessment of sedimentation trends and patterns for the study area. The primary focus in the study has been on historical rates of lake-sediment accumulation derived from ^{210}Pb analysis of sediment core samples from the lakes. Variables to describe the landscape and land-use histories were extracted from a GIS database developed to inventory the study catchments. The key findings are reviewed in the four points below:

- There is a clear trend towards increasing lacustrine sedimentation rates irrespective of land-use change in many of the lake catchments. About half of the control lakes in the study clearly show increasing sedimentation rates over the last 50 years, with increases ranging from 30 to 167% above background levels. This natural trend is a major confounding factor in disentangling land-use impacts on sedimentation patterns. This trend may be related to precipitation increases undergone in the whole study area over the last few decades.
- Natural disturbances, such as mass wasting and other geomorphic events, are important processes of sediment transfer in headwater lake catchments. Sedimentation-rate profiles from all physiographic regions show some periods of disturbed sediment accumulation where accumulation rates are temporarily elevated many times above background levels. These occurrences are most frequent in mountainous regions. A large amount of the total sediment load delivered to lakes can be deposited over relatively short periods of time during these episodic events.
- Lake basins are differentiated by physiography, both in terms of average specific sediment yield and dominant processes of sediment transfer, as indicated in the relation between drainage basin area and specific sediment yield. Highest sediment yields were observed in the North Coast mountains where specific sediment yield increases with increasing drainage area. This trend is likely associated with the dominance of

secondary remobilization of Quaternary sediments from streambanks and valley-bottom areas. In the flat-lying plateau and major valley areas, specific sediment yield decreases with increasing drainage area, thus fitting the conventional model of sediment delivery where storage efficiency increases downstream. In the Hazelton and Skeena mountains there is no significant relationship between specific yield and drainage area. These results suggest that no single sediment-yield model is adequate in describing the sediment-transfer processes in British Columbia at the sub-regional scale.

- Superimposed on all of the observed natural variability are some qualitative and semi-quantitative land-use effects on sediment yield. Land-use impacts could be only partially separated from natural fluctuations; however, a land-use signature, in the form of increased sedimentation rates, was observed in some of the study lakes. Largest increases have occurred in heavily harvested and roaded lake catchments in the Nechako Plateau and the Nass Basin and Major Valley regions. Significant increases were observed in basins that were subject to multiple land-use disturbances.

There are many ways in which this current research on lake sedimentation in northwestern British Columbia could be improved and further expanded. Temporal trends may be better explained by looking at storm frequency and flood-discharge records for the region. All of the catchment information in this study was based on remotely sensed sources, primarily aerial photographs. It would be useful to expand the field component and include more detailed aerial-photograph analysis in future projects to conclusively determine, and perhaps quantify, the sediment sources, transport capacity, intermediate storage sites, and lake-storage efficiency in the lake-catchment sedimentary system. This would be beneficial in establishing underlying physical processes and cause-and-effect relations between catchment conditions and lake-sediment signatures. There would be many advantages in expanding this project to a multi-core study format for a sub-set of lakes. A single-core approach was used because the large number of lakes included in the study would have made a multiple-core approach impractical because of the much higher associated costs and time requirements. A multiple core study would enable a better assessment of within-lake spatial variability, which is important in lakes with more complex morphometries. Errors associated with the ^{210}Pb dating and other measurements could be better described if replicate cores were available. A major advantage with the multiple-core approach is that absolute sediment yields could be estimated to a much higher degree of accuracy. The study could also be expanded to include a greater range of spatial scales and physiographic regions. Study results indicated that the relationship between the drainage basin area and specific sediment yield is variable in the different physiographic regions in northwestern British Columbia. This relationship is linked to downstream storage effects and remobilization of Quaternary sediment deposits, and holds major implications for geomorphological theory and for studies on land-use effects on the sedimentary system. It would be useful to expand the study data set so that the specific sediment-yield models for the province could be further refined.

The database of lake-sediment–based profiles of sediment yield, coupled with the operational GIS inventories of the contributing catchment areas, is a valuable and unique data set. To the knowledge of the authors, a comparable database of long-term, sediment-yield patterns and historical catchment conditions does not exist. It is anticipated that additional information about sediment-transfer processes in lake catchments can be extracted from this database by the use of more advanced statistical analysis. The next step of this ongoing research project is to use multivariate techniques to develop empirical models to predict sediment-loading rates in both the natural and disturbed state for lake catchments in northwestern British Columbia. The ultimate goal is to establish a set of tools to be used by operational planners to help minimize the impact of proposed land-use management activities on aquatic lake ecosystems.

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Regional Incidence of Landslides

PETER JORDAN

ABSTRACT

A regional study was made of landslides in portions of the Arrow Forest District and the Kootenay Lake Forest District, which permits some preliminary conclusions to be made about the areal frequency of landslides, their causes, and their importance as sediment sources to streams. The study covered all or parts of 100 map sheets, totaling about one million hectares. Approximately 1700 landslides were inventoried by air-photo interpretation. A subset of about one-quarter of this study area, centred on the Slocan Valley, is discussed in this paper.

The data show that landslide frequencies are typically increased by roughly 10 times by forest development (depending on how one defines the land base for calculation of areal frequencies). The landslide frequency on private land is higher than on Crown land. About 95% of development-related landslides are due to roads or skid trails. On older roads, road-fill failures are apparently the most common cause. However, on newer roads, the most common cause is drainage concentration and diversion by roads. An important category of landslides occurs some distance below roads, below a culvert or a point of accidental drainage discharge. In many of these cases, the road itself is on gently sloping, low-hazard terrain, and the landslide occurs on steeper terrain below. This is known as the "gentle-over-steep" situation. The Forest Practices Code does little to reduce landslide hazard in this situation, because the need for professional engineering involvement in road design is triggered by the hazard at the road location, not below the road.

The terrain type most frequently involved in landslides, on an areal basis, is deep glaciofluvial or other stratified glacial deposits in valley bottoms. Otherwise, there are few generalizations that can be made about terrain factors contributing to landslide hazard, or about contributions of landslide sediment to streams. Landslides, like other geomorphic and hydrologic processes, tend to follow magnitude-frequency relations. Small landslides are most frequent, and often do not reach a stream. Large landslides are much less frequent, but often enter streams. In most watersheds, landslides are not a major component of the sediment budget, but in the rare cases where a large landslide occurs, it can dominate the sediment regime for 1 or several years.

INTRODUCTION

A regional study was made of landslides in portions of the Arrow Forest District and the Kootenay Lake Forest District, which permits some preliminary conclusions to be made about the areal frequency of landslides, their causes, and their importance as sediment sources to streams. The main purpose of the study was to determine the terrain attributes most responsible for development-related landslides, and to use this information to improve classification criteria for terrain stability mapping.

The study covered all or parts of 100 map sheets, totalling about one million hectares. Approximately 1700 landslides were inventoried by air-photo interpretation; of these, a subset of about 200 was field checked. These data were supplemented with information on recent landslide events reported to the Engineering Section of the Nelson Forest Region of the B.C. Ministry of Forests.

The landslide inventory includes all landslides visible on air photos, development-related or natural, which are of types commonly caused by forest development. This includes all first-time debris slides, debris avalanches, and debris flows originating from an identifiable source, as well as slumps and rockslides that appear to be first-time events. Not included were chronic or long-lived failures, such as: slump-earthflows, deep-seated bedrock slumps, repeating debris flows that originate in diffuse channel or rockfall sources, chronic rockfall and ravelling on obviously unstable, non-forested slopes, and similar mass movement features.

LANDSLIDE INVENTORY IN ARROW AND KOOTENAY LAKE FOREST DISTRICTS

With the objective of summarizing part of the data that are useful in assessing the risk of landslides affecting populated areas and domestic-use watersheds, a subset of the data was selected, consisting of 24 map sheets centred on the Slocan Valley. This study area totals about 386 000 ha, and includes 582 landslides. Of these, 447, or 77%, are apparently related to development.

Table 1 is a summary of some of the study area statistics, the apparent causes of landslides, and estimated landslide densities. The "apparent cause" is based on air-photo interpretation, and is the apparent primary cause in the opinion of the mapper. These estimates are only an approximation of the actual causes of landslides; causes can be obtained for a small proportion of landslides as derived from engineering reports based on field inspections, and occasionally from field checks done as part of this study. Data on the approximate sizes of the landslides are also included. Considering the distribution of landslides by size classes, it is apparent that the number of landslides in the smallest size class may be underestimated. This is not surprising, as landslides smaller than 0.05 ha are difficult to see on the air photos, and clearly visible evidence of smaller landslides may disappear after a few years.

Our database includes more information on each landslide, including the apparent or known date, slope and aspect, bedrock geology, terrain type

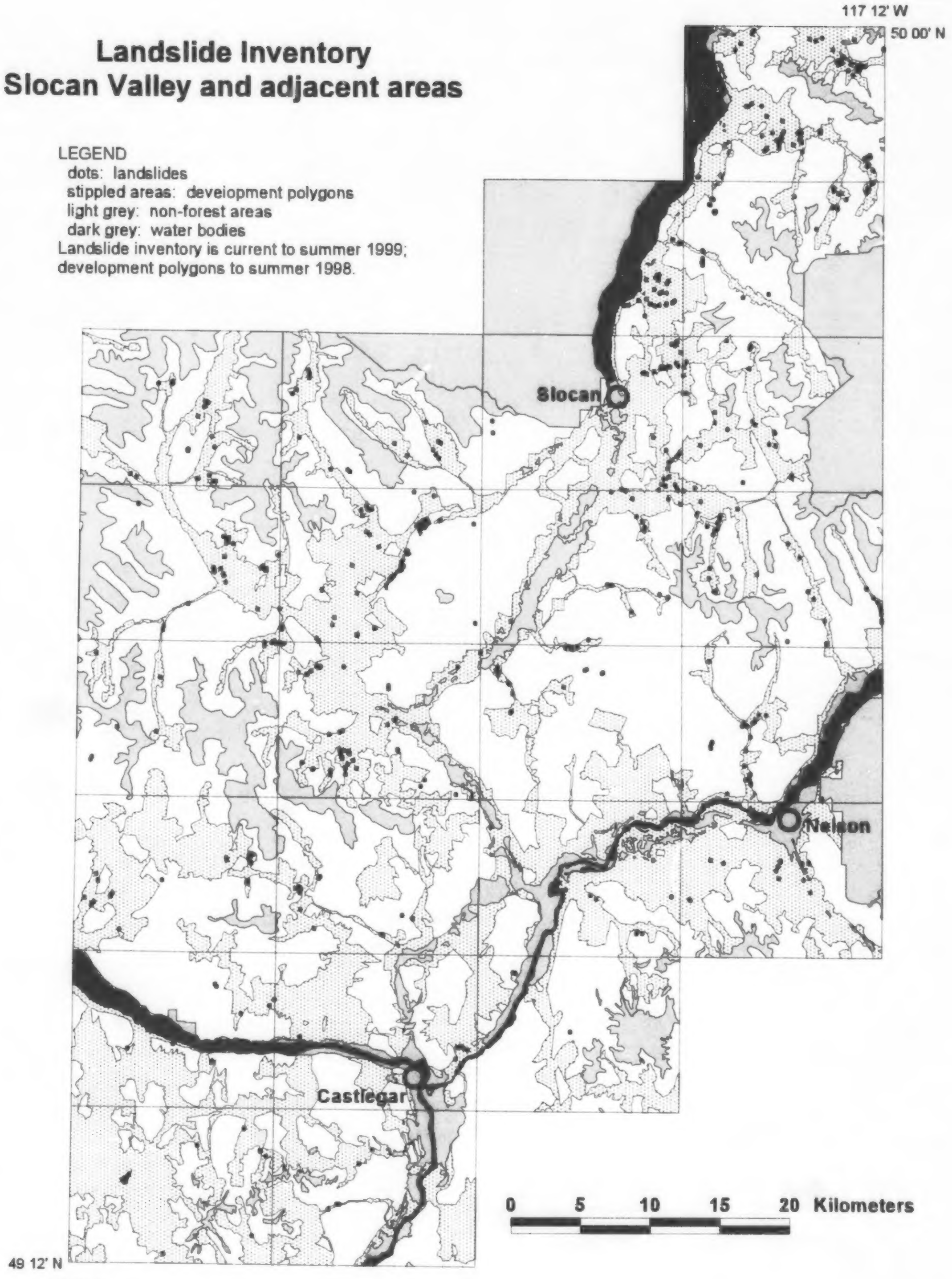
TABLE 1 *Summary of data from landslide inventory, Arrow and Kootenay Lake forest districts*

Area statistics	
Slocan Valley and adjacent sub-areas: 24 map sheets, total area	386 000 ha
Net forested area (excluding parks, alpine areas, farmland, etc.)	298 000 ha
Area included in development polygons	110 000 ha
Landslide statistics	
Total number of landslides	582
Natural	135
Development-related	447
Distribution by size class	
1 (0.02–0.05 ha)	25%
2 (0.05–0.2 ha)	43%
3 (0.2–1 ha)	30%
4 (1–5 ha)	2%
5 (> 5 ha)	0%
Distribution by apparent cause	
Road fill	36%
Drainage diversion, road	25%
Drainage diversion, skid trails	8%
Road cut	2%
Clearcut	2%
Other	4%
Natural	23%

interpreted from air photos, and type of failure. Further GIS and statistical analyses of the data are in progress.

Although analysis of the data set has not yet been completed, some trends are apparent from the field checking that was done along with terrain mapping in several detailed sub-areas. On older roads, fill failures were the most important cause of landslides. On newer roads, fill failures are uncommon, because under the Forest Practices Code there have been significant improvements to engineering standards aimed at preventing road-fill failures. However, on newer roads, drainage concentration and diversion are the primary causes of landslides. Of the terrain types common in the study area, deep glaciofluvial deposits and other deep stratified glacial (or kame) deposits in valley bottoms appear to be the most susceptible to landslides. There is apparently a greater frequency of landslides from logging on private land than on Crown land. This is due to the widespread use of excavated skid trails on steep slopes, and a lack of drainage control and deactivation on roads and trails; these practices are not allowed on Crown land.

Map 1 shows the study area and the distribution of landslides. It also shows "development polygons," which consist of logged areas, roads, and all areas below these, down to the nearest water course or valley bottom. In effect, this is the "hydrologic shadow" of roads and cutblocks. This is a more meaningful measure of the area of development than the area of harvesting


Landslide Inventory
Slocan Valley and adjacent areas
LEGEND
dots: landslides
stippled areas: development polygons
light grey: non-forest areas
dark grey: water bodies
Landslide inventory is current to summer 1999;
development polygons to summer 1998.
117 12' W
50 00' N
Slocan
Nelson
Castlegar
0
5
10
15
20
Kilometers
49 12' N
118 00' W

MAP 1 *Map showing the landslide inventory in the Slocan Valley sub-area. The grid outlines the* TRIM *6 x 12′ map sheets.*

would be; relatively few landslides occur in cutblocks, but many occur below cutblocks and roads. The development polygons were identified from a satellite photo, overlain with contours and water courses, using a GIS program (ArcView).

From the data presented in Table 1, some preliminary estimates of areal landslide density can be made. The net forest area is approximately 298 000 ha (excluding alpine areas, parks, water bodies, and urban/agricultural areas). Of this, about 110 000 ha are included in the development polygons. Roughly one-half of the study area is flat or gently sloping land (less than about 30%), and therefore is not subject to landslides. It can be assumed that, very roughly, the total forest land base of steeper land is about 150 000 ha, of which about 50 000 ha are in development polygons. (Stratification of the data by slope classes has not yet been completed.) Assuming that the data set represents landslides that have occurred over a 30-year period, this results in roughly estimated landslide densities of 0.003 natural landslides/km^2/y and 0.03 development-related landslides/km^2/y. It is noteworthy that almost all (at least 95%) of the development-related landslides are due to roads and skid trails; very few are caused directly by timber harvesting. It can be tentatively concluded that forest development, and in particular roads, increase landslide frequency by a factor of about 10 over natural rates.

These landslide frequencies are much lower than have been reported in terrain attribute studies conducted on the coast. Overall, development-caused landslide frequencies reported by Rollerson and Millard (1998) for study areas on western Vancouver Island and the Queen Charlotte Islands are approximately 0.5 and 1.1 landslides/km^2/y, respectively (calculated from the reported frequencies divided by the 15-year time span of the data set). Similar changes in landslide frequency due to forest development have been reported in the coastal studies. For example, in studies on the western Queen Charlotte Islands, post-logging landslide rates were 15 or more times as great as natural rates (Schwab 1998).

An important concept to understand is that landslides, like other geomorphic and hydrologic processes, tend to follow magnitude-frequency relations. Small landslides are most frequent, and often do not reach a stream. Large landslides are much less frequent, but often enter streams. A range of landslide sizes and runout distances is possible, and is often unpredictable at any given site.

In this study, approximately one-tenth of the landslides can be considered "very damaging," which means that they caused major damage to a stream, or were capable of presenting a risk to downslope inhabited areas. (Most landslides in the inventory were small, or stopped on a forest road, or stopped in timber on the lower slope. Obviously, the judgement of how many landslides are "very damaging" or "significant" is highly subjective.) If one assumes that each of these landslides contributes about 300 t of fine sediment to a stream (again, this is very approximate, but reasonable considering the average size is about 0.2 ha, and the fact that only about one-fifth of the volume of most landslides is fine sediment) then this would amount to an average fine sediment yield of about 1 t/km^2/y across the landscape. This is, of course, only an order-of-magnitude estimate. This can be compared to typical, suspended sediment yields, for low geomorphic activity watersheds typically used for community water supply, of about 1–20 t/km^2/y (Henderson and Toews, this publication; Jordan, this publication). Development-related landslides, therefore, appear on average to be a minor but not inconsequential component of the sediment budget of creeks in this region.

However, landslides can be a dominant component of the sediment budget locally and in certain years, as they are a highly episodic process. For example, in 1996, a large landslide deposited at least 5000 m^3 of sediment in Fortynine Creek, a 25-km^2 watershed near Nelson (Figures 5 and 6). If 1000 m^3 or 1500 t of this was suspended sediment deposited in the creek, and if it is assumed that the background suspended sediment yield was 5 $t/km^2/y$, then this event would represent about 12 times the typical annual sediment yield. In fact, in 1997, turbidities of 20–3000 NTU were measured during the peak snowmelt period, due to reworking of slide debris deposited in the channel and erosion of disturbed banks (no measurements were taken in 1996). In 1996, water quality was severely affected, and many water intakes were damaged by channel changes resulting from the influx of coarse sediment. This is an extreme and unusual example; however, it illustrates how large landslides, if they occur, can dominate the sediment budget for several years.

"GENTLE-OVER-STEEP" LANDSLIDES

An important category of landslides in our inventory consists of landslides that occur on steep or potentially unstable slopes, below a point of drainage discharge on a road on gentler terrain above. These are known locally as "gentle-over-steep" landslides. Many of the landslides attributed to road drainage fall in this category. Most often, they occur below a culvert, but also often occur below a switchback, a cross-ditch, or a point of unintended drainage diversion. Typically, the failure occurs at a break in slope, where the slope increases to about 50–70%, often on terrain that would be mapped by most terrain mappers as Stability Class III. They are equally likely to occur in forest as in harvested areas. Usually they occur during the snowmelt season, at a time when the snow line is close to the elevation of the road, and snowmelt rates are at their maximum (Toews 1991; Jordan and Toews 1993). Sometimes, the supply of water is enhanced by more rapid snowmelt in clearcuts above the road. Many of the largest and most mobile landslides in our data set are of this "gentle-over-steep" category.

The mechanism responsible for "gentle-over-steep" landslides is shown in the sketches of Figures 1 and 2. In the absence of defined gullies or other surface drainage pathways, water on a hillside tends to move downslope in a dispersed matter, often as shallow subsurface stormflow through a thin layer of weathered till or colluvium overlying relatively impermeable, dense, glacial till or bedrock. When a road is built across the slope, much of this flow can be intercepted by the road cut and ditch, and carried to cross-drain culverts. The water is then concentrated in narrow plumes below the culverts. This has two possible effects. One is that if the concentrated flow of water happens, by chance, to coincide with a location that is less stable than average—for example, because of locally steeper slopes, thin soil, or converging subsurface flow paths—and that has not experienced a high flow of water in the past, then a landslide is likely. The second effect is that the plume of water can "pre-soak" a long, narrow triangle of soil, raising the pore water pressure to near-critical values. If something occurs to trigger a small failure at a point near the top of the plume, then a very large debris avalanche can occur.

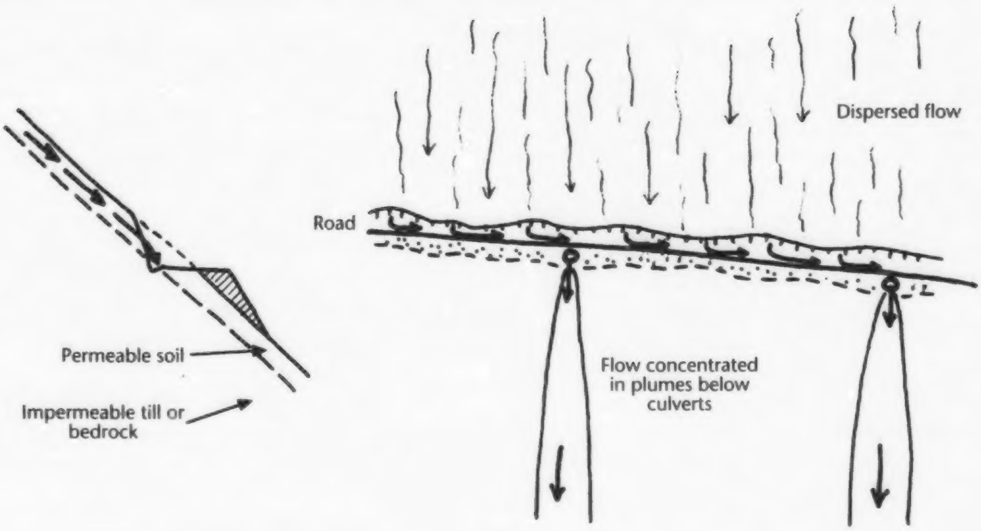

Dispersed flow
Road
Permeable soil
Impermeable till or bedrock
Flow concentrated in plumes below culverts

FIGURE 1 *Sketch showing the typical effect of roads and culverts on slope hydrology, for uniform slopes with shallow soils and low drainage density.*

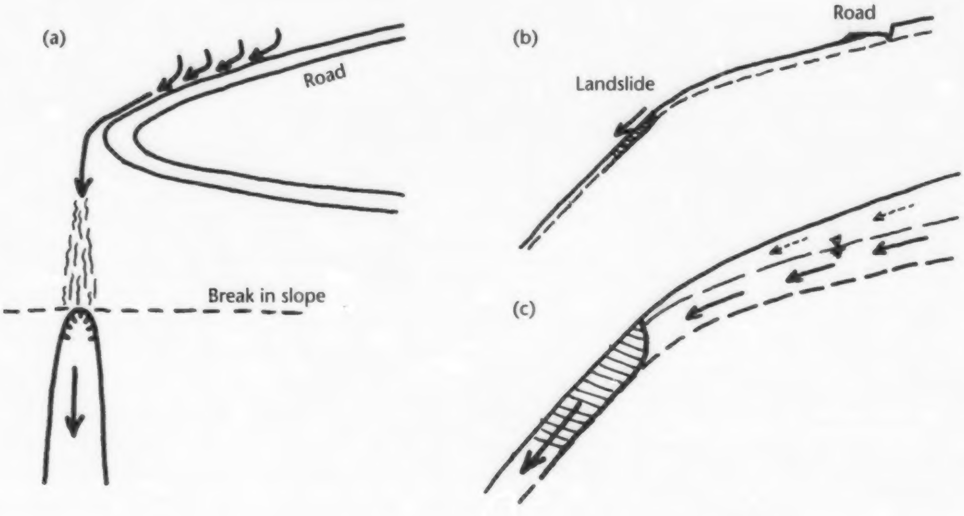


FIGURE 2 *Sketch showing the typical role of a road drainage diversion in triggering a "gentle-over-steep" landslide. (a) Plan view, landslide below a switchback. (b) Cross-section showing typical point of landslide initiation. (c) Enlargement, showing convergence of groundwater due to thinning soil depth at break in slope.*

Figure 2 shows in more detail the topographic conditions that favour such landslides. Often, the failure point occurs at a break in slope, where the slope locally increases to some critical value—typically over 60% but occasionally as low as 45%. Often, these steeper slopes are localized, and do not show up on contour maps where the average slope is gentler. Also, at a break in slope, or on a convex slope, the soil depth often decreases downslope, as more rapid soil creep on the steeper slope causes thinning over time. This results in converging groundwater flow paths, as subsurface flow is squeezed into a narrower layer of soil, and can result in locally greater pore water pressures at the break in slope.

Figure 3 illustrates a typical, although larger-than-average, example of a gentle-over-steep landslide (which occurred outside the study area, southeast of Nelson). Figure 4 shows a location near Slocan where, in May 1990, several landslides and debris flows were triggered below an area where extensive roads and logging covered a gentle plateau above (Curran et al. 1990). The

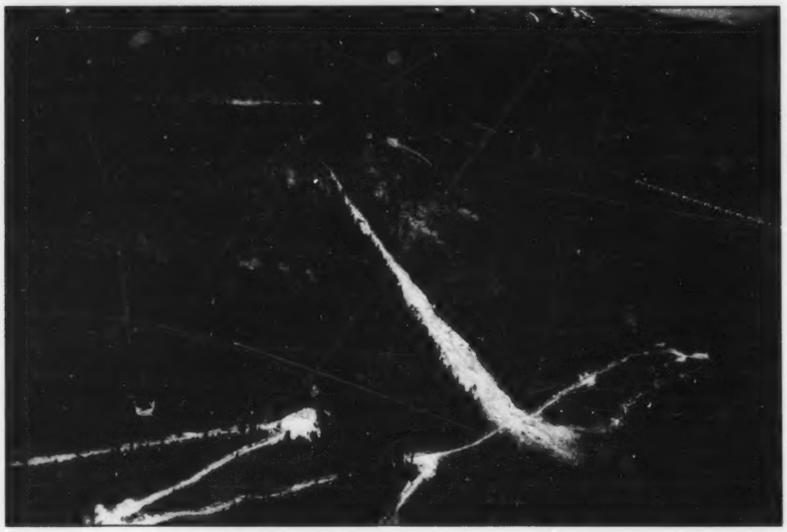


FIGURE 3 *A "gentle-over-steep" landslide, Shaw Creek, Kootenay Lake Forest District. Note road and skid trails above landslide.*

FIGURE 4 *Cape Horn area, Slocan Lake, Arrow Forest District. In 1990, several landslides and debris flows occurred in the gullies below the logged area.*

roads and skid trails had not been deactivated, and some local drainage basins above slide-initiation points had their drainage areas increased by more than double. Several water intakes and private properties, as well as the highway, were damaged by the debris flows. This incident, and several others in the late 1980s (Chow 1988) led to recognition of the "gentle-over-steep" hazard, and also led to significant improvements in road-engineering standards, planning, hazard mapping, and deactivation procedures in the region in the 1990s.

Figures 5 and 6 show the Fortynine Creek landslide of 1996, mentioned above, which seriously affected an important domestic watershed (over 50 water licenses) near Nelson. This landslide occurred below a culvert, which carried an unusually large volume of water, and was probably enhanced by diversion and concentration of water by upslope roads and skid trails. The failure point occurred where the slope steepened to 60% and the soil thinned downslope, as shown in Figure 2. On reaching a steep tributary, the landslide triggered a large debris flow, which continued for 1.2 kilometres until it reached the main creek channel.

FIGURE 5 *Fortynine Creek landslide. The road and culvert responsible for the slide are hidden behind the trees below the cutblock.*

FIGURE 6 *Fortynine Creek landslide, showing lower end of slide, and debris flow that travelled to the main creek.*

A concern regarding risk management of these landslides is that the Forest Practices Code usually does not require professional field assessments of terrain stability, or any special engineering design, when a "gentle-over-steep" situation exists. The need for professional assessments or other measures is triggered by terrain conditions at the site of the road, not on slopes below the road. Therefore, many potentially hazardous situations, where drainage concentrations occur above potentially unstable slopes, go unrecognized.

CONCLUSIONS

Preliminary results of the landslide inventory in Arrow and Kootenay Lake forest districts show that forest development increases landslide frequency, probably in the order of 10 times over natural rates. Landslide frequencies in this region are much lower than those reported in coastal British Columbia. Most landslides in the region are caused by roads. Clearcuts are not an important direct cause of landslides. However, clearcuts sometimes indirectly increase the hazard of landslides caused by drainage concentration, by enhancing snowmelt rates.

Drainage diversion and concentration by roads are the most important causes of landslides on the newer roads. Many landslides are caused by "gentle-over-steep" drainage concentrations; these landslides are significant because they can be very large and can occur on slopes not suspected of being potentially unstable, and because the hazardous situation may go unrecognized, because professional assessments and engineering design are often not required by the Forest Practices Code.

On a watershed scale, the location of roads is clearly an important factor in assessing landslide risk, more so than the rate of cut or the equivalent clearcut area (ECA). In assessing watersheds, either pre-development or for deactivation planning, an important objective should be to identify high-risk roads. These are often roads in low-hazard terrain with higher-hazard slopes below, and not identified as high risk by existing procedures. Planning and assessments should focus on drainage plans for new roads, or deactivation of old roads, in these high-risk locations.

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